Stantec

Projet de valorisation de matières dangereuses résiduelles à l'aide d'un procédé de désorption thermique anaérobie sur le territoire de la municipalité de Contrecœur par Triumvirate Environmental inc.

Questions et commentaires – 2e série (octobre 2022)

Préparé pour :

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Direction générale de l'évaluation environnementale et stratégique

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Les conclusions du Rapport, intitulé *Questions et commentaires (2e série – octobre 2022) - Projet de valorisation de matières dangereuses résiduelles à l'aide d'un procédé de désorption thermique anaérobie sur le territoire de la municipalité de Contrecœur par Triumvirate Environmental inc.,* reflètent l'opinion professionnelle de Stantec au moment de la rédaction du Rapport et concernent la portée du mandat décrite dans le Rapport. Les opinions contenues dans ce document sont basées sur les conditions et les informations existantes au moment de la publication du document et ne tiennent compte d'aucune modification ultérieure. Le Rapport ne concerne que le projet pour lequel les services de Stantec ont été retenus et l'objectif énoncé pour lequel le Rapport a été préparé. Le Rapport ne doit pas être utilisé afin de modifier ou de prolonger le projet, ou à tout autre fin ou projet, et toute utilisation non autorisée par quiconque est aux risques de ce dernier.

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1.0 MISE EN CONTEXTE

1.1 JUSTIFICATION DU PROJET

QC - 1

À la question QC-3d, l'initiateur a mentionné que seront traités dans l'ATDU le type de matière suivante : « O02 : autres matières non dangereuses » aux codes de « MDR ». L'initiateur doit fournir de l'information sur la teneur ou la nature de cette matière. Le Règlement sur l'enfouissement et l'incinération de matières résiduelles (REIMR) pourrait s'appliquer à la technologie de l'initiateur si elle était utilisée pour des matières résiduelles au sens du REIMR.

Réponse QC-1 :

Nous ne proposons pas de traiter des déchets domestiques (ordures ménagères), ou des boues sanitaires dans l'unité, donc le chapitre III du REIMR ne s'applique pas. Les matières qui seront traitées dans l'ATDU sont uniquement des matières que le site est déjà autorisé à recevoir dans le permis 7610-16-01-0648634.

2.0 AMÉNAGEMENT DES INSTALLATIONS DU PROJET ET DU SITE

QC - 2

L'entreprise n'a pas fourni « les caractéristiques de l'abri qui protégera les équipements du procédé. Ainsi, il doit donner les caractéristiques de l'abri et démontrer que ce dernier répond aux exigences du RMD ».

Réponse QC-2 :

Les exigences du RMD s'appliquent à divers modes d'entreposage, or ce qui sera placé sous un abri dans le cadre de ce projet sera plutôt des équipements de procédé. Des équipements dont la fonction ne sera pas d'entreposer des matières dangereuses, mais où cette dernière sera en mouvement et en changement de phase (entre les phases liquide et vapeur). L'abri consiste en un toit supporté par une structure métallique.

3.0 ACTIVITÉS DE LA PHASE DE CONSTRUCTION

QC - 3

À la question QC-21, l'équipe d'analyse a demandé à l'initiateur de fournir des détails concernant la période de mise à l'essai. Dans ce contexte, l'initiateur devait fournir le type de MDR qui seront utilisées, les étapes prévues de la mise à l'essai, le calendrier de réalisation et les critères de réussite de cet essai. Il a aussi été demandé à ce que l'initiateur détaille les mesures qui seront prises et les étapes subséquentes pour le projet si les critères de réussite de l'essai ne sont pas atteints.

L'initiateur a fourni la procédure de démarrage du procédé. Or, aucune information n'a été donnée relativement aux autres informations requises. L'initiateur doit fournir les éléments manquants.

Réponses QC-3 :

Dans la cadre des activités de mise à l'essai du procédé, les matières dangereuses résiduelles (MDR) qui seront utilisées seront du même type que celles qui seront traitées lors de l'opération du procédé, soit les types de MDR identifiées à la sous-section 3.1.4. du rapport d'étude d'impact sur l'environnement de Stantec (novembre 2020) transmis au ministère. Par conséquent, les MDR utilisées lors de la mise à l'essai seront vraisemblablement une combinaison de flacons de laboratoire (« lab packs »), de contenants divers contaminés par une substance organique faits de métal ou de plastique et de chiffons souillés de substances organiques (par exemple de l'huile ou des solvants). Il n'est pas possible à l'heure actuelle d'être plus précis sur les matières résiduelles qui seront utilisées et dans quelles proportions, puisque cette étape du projet demeure loin dans l'échéancier du promoteur (la conception finale du projet n'est pas encore complétée).

Typiquement, les étapes de mise à l'essai pour ce procédé sont les suivantes : tri et classification des MDR introduites dans le procédé, traitement des MDR dans le procédé et analyse des solides générés par l'unité de désorption thermique anaérobie (ci-après « ATDU »), soit les résidus riches en carbone et des débris métalliques. Les analyses des résidus solides visent à confirmer qu'ils peuvent être gérés comme des matières non dangereuses et expédiés hors site à un lieu d'enfouissement technique ou valorisés comme source de combustible de remplacement. Les analyses menées seront des essais de lixiviation pour les matières poreuses (soit les résidus riches en carbone) et l'analyse d'échantillons de frottis pour les surfaces non poreuses (soit les pièces métalliques). Les résultats d'analyses seront ensuite comparés aux critères de l'article 3 du règlement sur les matières dangereuses (RMD) et de la fiche d'information du MELCCFP nommée « Matériaux de démantèlement et contamination de surface »[1].

Le critère principal de réussite de la mise à l'essai est de générer des résidus solides qui peuvent être gérés comme de la matière résiduelle non dangereuse. Le critère secondaire est d'obtenir un ratio de liquide-gaz le plus élevé possible, c.-à-d. de condenser le maximum de vapeur organique générée dans l'ATDU en huile organique. Si le critère principal n'est pas atteint, de nouvelles mises à l'essai seront effectuées en ajustant les paramètres d'opération de l'ATDU, soit la température de traitement et le temps de résidence de la matière résiduelle introduite, dans le but de favoriser l'évaporation des substances organiques, et leur séparation de la matière solide. Le critère secondaire, bien qu'il ne soit pas un élément critique pour la réussite de la mise à l'essai, pourra être utilisé pour optimiser l'opération de l'unité de récupération des vapeurs où la condensation de ces dernières est réalisée à l'aide d'eau refroidie. Ce procédé est éprouvé et le manufacturier retenu par Triumvirate (RLC Technologies) a fourni les équipements pour plus de 25 installations réparties dans une douzaine de pays à travers le monde. Il n'est donc pas appréhendé que les mises à l'essai mènent à la conclusion que cette technologie n'est pas appropriée pour le traitement des matières résiduelles visées.

[1] https://www.environnement.gouv.qc.ca/matieres/dangereux/demantelement.pdf

Le processus de mise à l'essai pour ce procédé est généralement réalisé dans les 3 mois précédant la mise en service du procédé et ce sera le cas également pour le procédé installé par Triumvirate à Contrecœur.

4.0 SYSTÈME DE GESTION DES EAUX DE SURFACE

QC-4

À la question QC-12, l'initiateur mentionne que, lors de la phase de construction et d'exploitation, la qualité des eaux pluviales sera comparée aux critères de résurgence dans l'eau de surface. Toutefois, cette façon de faire n'est pas adéquate puisque ce critère s'applique pour des eaux souterraines qui font résurgence dans l'eau de surface et non à de l'eau pluviale qui s'écoule en surface. Par conséquent, l'initiateur doit :

a) s'engager à comparer la qualité de l'eau pluviale aux exigences suivantes qui sont celles habituellement demandées pour des eaux pluviales contaminées sur des sites industriels : pH : 6,0-9,5, MES : 50 mg/l et hydrocarbures pétroliers C10-C50 : 2,0 mg/l.

b) dans le cas des autres contaminants identifiés susceptibles de se retrouver dans les eaux pluviales, soit les COV et les HAP, l'initiateur doit identifier dès maintenant des composés plus spécifiques à analyser, par exemple, le benzène.

Réponse QC-4 :

a) Triumvirate s'engage à utiliser les critères de qualité de l'eau de surface susmentionnés pour le pH, les MES et les hydrocarbures pétroliers C10-C50 lors de son évaluation des résultats d'analyse des échantillons d'eaux pluviales.

b) Les composés spécifiques analysés pour les COV seront les suivants :

• Acétone	• 1,3-Dichlorobenzène	• Éthylbenzène	• Tétrachloroéthylène
• Benzène	• 1,4-Dichlorobenzène	• Dibromure d'éthylène	• Toluène
• Bromodichlorométhane	• Dichlorodifluorométhane	• *n*-Hexane	• 1,1,1-Trichloroéthane
• Bromoforme	• 1,1-Dichloroéthane	• Méthyléthylcétone	• 1,1,2-Trichloroéthane
• Bromométhane	• 1,2-Dichloroéthane	• Chlorure de méthylène	• Trichloroéthylène
• Tétrachlorure de carbone	• Dichloroéthylène	• Méthylisobutylcétone	• Chlorure de vinyle
• Chlorobenzène	• cis-1,2-Dichloroéthylène	• Éther tert-butylique méthylique	• m,p-Xylènes
• Chloroforme	• trans-1,2-Dichloroéthylène	• Styrène	• o-Xylène
• Dibromochlorométhane	• 1,2-Dichloropropane	• 1,1,1,2-Tétrachloroéthane	• Xylènes, total
• 1,2-Dichlorobenzène	• cis-1,3-Dichloropropylène	• 1,1,2,2-Tétrachloroéthane	

Cette liste de substances se veut un balayage des composés les plus communément retrouvés dans les solvants organiques reçus au site, selon les analyses effectuées sur ces derniers dans le cadre de cette étude d'impact.

Les composés spécifiques analysés pour les HAP seront les suivants :

• Acénaphtène	• Benzo[*b+j*]fluoranthène	• Fluoranthène	• Naphtalène
• Acénaphtylène	• Benzo[g,h,i]pérylène	• Fluorène	• Phénanthrène
• Anthracène	• Benzo[k]fluoranthène	• Indeno[1,2,3-cd]pyrène	• Pyrène
• Benzo[*a*]anthracène	• Chrysène	• 1-Méthylnaphthalène	
• Benzo[*a*]pyrène	• Dibenzo[a,h]anthracène	• 2-Méthylnaphthalène	

QC-5

L'initiateur doit s'engager à préciser lors de la demande d'autorisation ministérielle en vertu de l'article 22 de la LQE, quelles mesures seront mises en place pour s'assurer qu'aucune eau pluviale contaminée ne sera rejetée à l'environnement lors de la phase de construction et d'exploitation.

L'initiateur devra notamment démontrer que les réservoirs, contenants, bassins ou autres servant à contenir les eaux pluviales ont une capacité d'entreposage suffisante, et ce en tenant compte de la récurrence de la pluie et des changements climatiques.

Réponse QC-5 :

Triumvirate s'engage à présenter dans sa future demande d'autorisation ministérielle les détails ci-dessus concernant la gestion de l'eau pluviale sur son site et les mesures de protection de l'environnement retenues relativement à l'eau pluviale potentiellement contaminée, et ce, pendant les phases de construction et d'exploitation du projet.

QC-6

À la question QC12, l'initiateur mentionne que si les eaux pluviales sont considérées comme contaminées, elles seront acheminées à un site de traitement par une entreprise de gestion de matières résiduelles autorisée pour la phase de construction.

L'initiateur doit s'engager à préciser vers quel type de site seront acheminées les eaux pluviales contaminées lors de la demande d'autorisation ministérielle en vertu de l'article 22 de la LQE.

Réponse QC-6 :

Triumvirate s'engage à préciser dans sa future demande d'autorisation ministérielle le(s) destinataire(s) à qui sera expédiée l'eau pluviale contaminée.

QC-7

L'initiateur doit s'engager à ce que les eaux pluviales soient déchargées de manière graduelle au cours d'une journée de manière à éviter de créer de l'érosion dans le fossé.

L'initiateur doit s'engager à préciser lors de la demande d'autorisation ministérielle en vertu de l'article 22 de la LQE, de quelle manière sera contrôlé le rejet des eaux pluviales non contaminées lorsqu'elles seront déchargées dans le fossé.

Réponse QC-7 :

Triumvirate s'engage à préciser dans sa future demande d'autorisation ministérielle le mode de gestion des rejets d'eaux pluviales non contaminées dans le fossé bordant le site.

QC-8

L'initiateur doit s'engager à mettre une méthode en place pour éviter le débordement du réservoir des eaux pluviales directement à l'environnement.

Le choix de la méthode (ex. : installation d'un trop-plein ou d'une alarme de haut niveau) devra être mentionné dans la demande d'autorisation ministérielle en verte de l'article 22 de la LQE.

Réponse QC-8 :

Triumvirate s'engage à préciser dans sa future demande d'autorisation ministérielle la mesure mise en place pour éviter les déversements du réservoir d'eaux pluviales contaminées dans l'environnement.

QC-9

L'initiateur doit s'engager à réaliser un suivi des vidanges des eaux pluviales, lors de la phase de construction et d'exploitation, qu'elles soient réalisées par l'envoi de réservoirs vers une entreprise spécialisée autorisée ou toute autre méthode autorisée. Le suivi devrait notamment comprendre la date, le volume rejeté et les résultats d'échantillonnage.

L'initiateur doit s'engager à déposer ces informations lors de la demande d'autorisation en vertu de l'article 22 de la LQE lors de chacune des phases visées.

Réponse QC-9 :

Triumvirate s'engage à décrire dans sa future demande d'autorisation ministérielle le suivi des vidanges d'eaux pluviales contaminées qui sera réalisé, notamment son contenu et le mode de documentation des informations.

5.0 ÉMISSIONS DE GES

QC-10

L'initiateur doit s'engager à informer le MELCC lorsque les mesures d'atténuation des émissions des GES qu'il a présentées seront déployées.

Réponse QC-10 :

Triumvirate s'engagera dans sa future demande d'autorisation ministérielle à informer le MELCCFP de l'échéancier de mise en œuvre des mesures d'atténuation.

6.0 MODÉLISATION DE LA DISPERSION ATMOSPHÉRIQUE

QC-11

Le taux d'émission des oxydes d'azote (NOx) de l'oxydateur thermique est basé sur le facteur d'émission de la section 1.4 AP_42 de l'USEPA. Ce facteur tient compte principalement du NOx thermique de l'oxydation de l'azote (N2) contenu dans l'air de combustion. Néanmoins, les gaz non condensables (GNC) incinérés dans le T.O.U contiennent également du N2 provenant du procédé (540 kg/h selon le bilan de masse).

L'initiateur doit préciser pourquoi l'oxydation thermique de l'azote du procédé n'a pas été considérée pour la détermination du taux d'émission des NOx pour l'oxydateur thermique. L'initiateur doit mettre à jour la modélisation atmosphérique s'il ne peut justifier ce choix.

Réponse QC-11 :

La formation de NOx par la réaction de l'azote du gaz d'inertage du procédé introduit dans l'oxydateur thermique avec l'oxygène de l'air de combustion n'a pas été considérée, car il a été jugé négligeable par rapport au phénomène de formation de NOx à la flamme du brûleur de l'oxydateur, entre l'azote et l'oxygène contenus dans l'air de combustion. La formation de NOx commence à devenir significative à des températures au-delà de 1300 °C, tandis qu'à des températures de l'ordre de 750 °C, la formation de NOx est très faible ou absente[2]. La chambre de combustion de l'oxydateur thermique utilisé dans le projet sera opérée de façon à maintenir une température d'environ 980 °C.

Selon la conception de l'oxydateur thermique qui sera utilisé dans le projet, les gaz non condensables (GNC), composés de substances organiques et du gaz d'inertage d'azote, seront alimentés dans la chambre de combustion à environ 2 mètres de la flamme du brûleur, tel que montré sur le plan de conception inséré à l'annexe A du présent document. Le gaz d'azote d'inertage n'est donc pas injecté directement dans la flamme du brûleur, là où la formation de NOx thermique est favorisée dû à la température élevée prévalant à cet endroit.

Néanmoins ce qui précède, une analyse de sensibilité a été effectuée sur les émissions de NOx de l'oxydateur thermique afin de valider l'hypothèse posée pour cette source d'émission. L'analyse s'est appuyée sur une étude[3] portant, entre autres, sur l'effet de la dilution à l'azote d'un gaz de méthane sur les émissions de NOx produites lors de sa combustion. Pour les fins de l'analyse de sensibilité, le mélange méthane-azote considéré dans cette étude a été assimilé au mélange de GNC et d'azote d'inertage du procédé du projet de Triumvirate. Les résultats de cette étude mettent en relation la fraction massique d'azote versus le taux de génération de NOx (ceci est représenté à la figure 3 de l'article publié pour cette étude). Selon le bilan de masse du projet, la fraction massique d'azote dans les gaz dirigés à l'oxydateur thermique est de 0,3 (540 kg/h d'azote sur 1798 kg/h de GNC et d'azote). Le taux d'émission de NOx correspondant à cette fraction massique est d'environ 0,43 g NOx/kg GNC selon le graphique de

[2] Selon les informations présentées dans le document suivant : Environmental Protection Agency (1999). *Technical Bulletin – Nirtogen Oxydes (NOx), why and how they are controlled*. (https://www3.epa.gov/ttncatc1/dir1/fnoxdoc.pdf)
[3] B.Fackler et Al. (2011). *Experimental and numerical study of NOx formation from the lean premixed combustion of CH4 with CO2 and N2* (https://www.researchgate.net/publication/267502406)

la figure 3 de l'étude. Il faut noter que ces données expérimentales ont été obtenues pour une température de combustion de 1800 K (environ 1500 °C), laquelle est plus élevée que la température à laquelle sera opérée la chambre de combustion de l'oxydateur thermique (980 °C). L'approche suivie est donc conservatrice, car la formation de NOx serait en réalité plus faible à une température de combustion de 980 °C.

Un taux d'émission de NOx, de 0,15 g/s, a donc été calculé à partir du taux d'émission estimé à partir des données expérimentales de l'étude (0,43 g NOx/kg GNC x 1257,6 kg GNC/h). Ce taux d'émission de NOx a été ajouté à celui généré par la combustion du gaz pilote dans le brûleur (0,025 g/s) pour une émission totale de l'oxydateur thermique de 0,175 g/s de NOx. Ce taux d'émission a été utilisé pour effectuer une nouvelle modélisation de la dispersion atmosphérique du NOx et les résultats sont présentés à l'annexe D. Les concentrations maximales prédites de NOx, incluant les émissions de l'oxydateur thermique et celles des brûleurs de gaz naturel de l'ATDU, sont inférieures aux normes (sur 1 heure, 24 heures et annuelle). Ces résultats indiquent que la contribution aux concentrations ambiantes des émissions de NOx qui pourraient être générées par la réaction entre l'azote du gaz d'inertage et l'oxygène résiduel dans la chambre de combustion n'est pas significative.

Les documents de référence utilisés pour répondre à cette question sont fournis à l'annexe B.

QC-12

Au tableau QC-59.2, l'initiateur présente les résultats de la modélisation pour tous les contaminants modélisés. Les activités de l'entreprise occasionneraient des dépassements pour trois normes et deux critères de qualité de l'atmosphère :

1. Acétate de n-butyle – 1 671 % de la norme* sur 4 minutes (fréquence de dépassements de 8 %);
2. Acide chlorhydrique – 117 % de la norme sur 4 minutes;
3. Acide nitrique – 2 101 % du critère sur 1 heure;
4. Toluène – 112 % de la norme sur 4 minutes;
5. Noir de carbone – 123 % du critère sur 1 heure.

Devant une telle situation, et en vertu de l'article 197 du Règlement sur l'assainissement de l'atmosphère, l'initiateur doit démontrer que le projet n'est pas susceptible d'engendrer une augmentation de la concentration dans l'air ambiant pour les contaminants dont la norme est déjà excédée. Pour y arriver, l'initiateur doit présenter deux modélisations : une première, selon les activités actuellement autorisées de l'usine (scénario avant-projet), et une seconde, selon les conditions d'opération projetées (scénario après-projet). Ce deuxième scénario doit inclure des mesures de mitigation qui démontrent que la réalisation du projet n'entraîne pas une dégradation de la qualité de l'air ambiant, si requis.

Dans le cas de l'acétate de n-butyle, l'initiateur doit présenter la concentration au 99e centile au pire point d'impact sur le domaine d'application des normes et critères et la fréquence de dépassements en ce point pour chacune des années modélisées. Les fréquences de dépassements modélisées doivent refléter l'horaire réel d'émissions de ce contaminant.

De plus, les résultats de l'étude de dispersion montrent que les critères de qualité de l'atmosphère de deux contaminants seraient excédés. L'initiateur doit proposer et intégrer à la modélisation toutes les mesures d'atténuation permettant de réduire les concentrations dans l'atmosphère de ces contaminants.

Réponse QC-12 :

L'approche proposée par le ministère a été suivie afin de démontrer que les concentrations ambiantes maximales produites par le projet sont inférieures à celles générées par les sources actuelles (préprojet). Donc, deux scénarios ont été modélisés, soit un scénario « préprojet » comprenant les sources d'émissions existantes, et un scénario « projet » comprenant les sources d'émissions du projet ainsi que les sources existantes qui demeureront actives. Il faut noter que certaines sources du scénario projet ont été modifiées pour cette mise à jour de la modélisation afin d'améliorer la dispersion atmosphérique des substances dont les concentrations ambiantes maximales dépassent leur valeur limite.

Le tableau QC-1 à la page suivante présente une description des sources visées pour ces deux scénarios. Les tableaux C1 et C2, insérés à l'annexe C, présentent les taux d'émissions de substances émises pour chaque source considérée pour les deux scénarios. Les résultats de la modélisation de la dispersion atmosphérique de chacun des scénarios sont présentés aux tableaux D1 et D2 de l'annexe D.

Des cartes isoplèthes ont été préparées pour les substances dont les concentrations maximales ambiantes dépassent leurs valeurs limites pour le scénario préprojet. Des cartes isoplèthes ont aussi été préparées pour ces mêmes substances pour le scénario projet afin de visualiser les réductions des concentrations ambiantes produites par le projet. Une carte a également été produite pour les concentrations ambiantes de noir de carbone (substance dont les concentrations maximales dépassaient les critères dans la dernière version du modèle de dispersion atmosphérique présentée au MELCCFP). Les cartes isoplèthes de concentrations décrites ci-dessus sont insérées à l'annexe E.

Selon les résultats présentés au tableau D2 à l'annexe D, on note que substances dont les concentrations maximales dépassaient leur valeur limite dans le cadre de la dernière modélisation présentée au MELCCFP[4], sont maintenant conforme, à une exception près (acide nitrique), grâce aux modifications apportées à certaines sources d'émissions dans le cadre du projet. Celles-ci ont consisté, entre autres, en la modification de l'orientation et de la hauteur des cheminées de certaines sources (postes de désemballage de « lab-packs » et de percement de cannettes aérosol) et à l'utilisation d'un matériel de filtration de particules plus performant dans le dépoussiéreur de résidus riches en carbone. Ces modifications sont décrites en détail dans le tableau QC-1.

[4] Stantec (août 2022). *Projet de valorisation de matières dangereuses résiduelles à l'aide d'un procédé de désorption thermique anaérobie sur le territoire de la municipalité de Contrecœur par Triumvirate Environmental inc. – Questions et commentaires* (Document de réponses). V/Réf. : 3211-22-017.

Tableau QC-1 Sources visées pour scénario préprojet et projet

N° Source	Description	Scénario préprojet	Scénario projet
1	Entreposage de « lab-packs » dans des armoires de sûreté	Source non retenue (voir réponse à la question QC-47 de la première demande d'information du MELCCFP [1]).	Source non retenue (voir réponse à la question QC-47 de la première demande d'information du MELCCFP [1]).
2	Poste de traitement de chiffons souillés	Source non retenue (voir réponse à la question QC-47 de la première demande d'information du MELCCFP [1]).	Source non retenue (voir réponse à la question QC-47 de la première demande d'information du MELCCFP [1]).
3 et 4	Poste de désemballage de « lab-packs » de produits chimiques	**Caractéristiques de la source existante :** - **Hauteur cheminée par rapport au sol : 4,572 m** - **Orientation : horizontale** - **Diamètre : 0,609 6 m** - **Vitesse des gaz : 4,85 m/s** **Dans ce scénario toutes les substances organiques et acides sont émises de cette source.**	**Caractéristiques de la source modifiée pour le projet :** - **Hauteur cheminée par rapport au sol : 12,32 m** - **Orientation : verticale** - **Diamètre : 0,304 8 m** - **Vitesse des gaz : 19,4 m/s** **Dans ce scénario, seuls les acides sont émis de cette source, car les tous les « lab-packs » contenant des substances organiques seront traités dans l'ATDU.**
5	Poste de pompage de barils de solvants usés	Source non retenue (voir réponse à la question QC-47 de la première demande d'information du MELCCFP [1]).	Source non retenue (voir réponse à la question QC-47 de la première demande d'information du MELCCFP [1]).
6	Poste de percement de cannettes aérosol	**Caractéristiques de la source existante :** - **Hauteur cheminée par rapport au sol : 4,572 m** - **Orientation : horizontale** - **Diamètre : 0,609 6 m** - **Vitesse des gaz : 4,85 m/s**	**Caractéristiques de la source modifiée pour le projet :** - **Hauteur cheminée par rapport au sol : 12,32 m** - **Orientation : verticale** - **Diamètre : 0,304 8 m** - **Vitesse des gaz : 19,4 m/s**
7	Laboratoire (instrument d'analyse par chromatographie en phase gazeuse et poste de manipulation)	Source non retenue (voir réponse à la question QC-47 de la première demande d'information du MELCCFP [1]).	Source non retenue (voir réponse à la question QC-47 de la première demande d'information du MELCCFP [1]).
8A et 8B	Parc de réservoirs d'entreposage de solvants usés (évents)	**Des émissions de substances organiques se produisent au niveau des évents de chacun des réservoirs, lesquels sont sous un abri sous forme d'un dôme en toile ayant ses deux extrémités ouvertes.**	Source non retenue (voir réponse à la question QC-53 de la première demande d'information du MELCCFP [1]).

Nº Source	Description	Scénario préprojet	Scénario projet
		Les émissions de substances organiques des évents des réservoirs ont été considérées émises par les deux extrémités du dôme, et ce, partagées également entre les deux (50/50). Celles-ci ont été considérées comme étant des sources volumiques dans le modèle de dispersion. Les dimensions initiales latérales et verticales calculées par le modèle AERMOD sont de 0,71 m et 1,7 m respectivement.	
9A et 9B	ATDU (Brûleurs au gaz naturel)	Source inexistante	**Nouvelle source du projet**
10	Oxydateur thermique	Source inexistante	**Nouvelle source du projet** **Les émissions de NOx ont été ajustées pour considérer des émissions potentielles issues de la réaction entre l'azote du gaz d'inertage et l'oxygène dans l'air de combustion (voir réponse à la question QC-11 pour les détails).**
11	Dépoussiéreur (pour résidus riches en carbone)	Source inexistante	**Nouvelle source du projet** **Des filtres plus performants ont été considérés en remplacement des filtres initialement prévus. Des membranes de type « ePTFE » (2) seront utilisées avec les filtres à sacs, lesquels permettent d'atteindre une concentration après filtration de 0,000 6 grain/pi^3 (1,4 mg/m^3). Le taux d'émission révisé pour cette substance est présenté dans le tableau C2 à l'annexe C.**
12	Réservoir d'huile organique (évent)	Source inexistante	Source non retenue (voir réponse à la question QC-53 de la première demande d'information du MELCCFP [1]).

Notes du tableau QC-1 :

(1) MELCCFP (2021). *Questions et commentaires pour le projet de valorisation de matières dangereuses résiduelles à l'aide d'un procédé de désorption thermique anaérobie sur le territoire de la municipalité de Contrecœur par Triumvirate Environmental inc.*, Dossier 3211-22-017, 16 février 2021.

(2) Source de l'information : https://www.baghouse.com/products/baghouse-filters/ptfe-filters/

Le tableau QC-2 suivant présente une comparaison des concentrations maximales, en termes de pourcentage des valeurs limites, avant et après les modifications apportées à certaines sources du scénario projet, et ce, pour les substances qui étaient non conformes à leur valeur limite.

Tableau QC2 Variation des concentrations maximales des substances non conformes pour le scénario projet

Substance	Scénario préprojet (1)	Scénario projet
Acétate de n-butyle	1 068 % de la norme sur 4 minutes	82 % de la norme sur 4 minutes
Acétate d'éthyle	1 282 % de la norme sur 4 minutes	2 % de la norme sur 4 minutes
Acide chlorhydrique	50 % de la norme sur 4 minutes	7 % de la norme sur 4 minutes
Acide nitrique	906 % du critère sur 1 heure	127 % du critère sur 1 heure
Chloroforme	2 445 % du critère sur 1 an	85 % du critère sur 1 an
Chlorure de méthylène	675 % de la norme sur 1 an	29 % de la norme sur 1 an
Éther de méthyle et de butyle tertiaire	292 % de la norme sur 4 min	0,2 % de la norme sur 4 min
Méthyle éthyle cétone	118 % de la norme sur 4 min	0,4 % de la norme sur 4 min
Toluène	108 % de la norme sur 4 minutes	47 % de la norme sur 4 minutes
Trichloroéthylène	169 % de la norme sur 1 an	75 % de la norme sur 1 an
Noir de carbone	123 % du critère sur 1 heure	37 % du critère sur 1 heure

Note du tableau QC-2 :

(1) La modélisation avec l'ajout de certaines sources d'émissions existantes du scénario préprojet a mené à des dépassements de valeurs limites pour de nouvelles substances, tandis que pour d'autres substances, les concentrations maximales prédites sont inférieures aux valeurs limites.

Le sommaire des résultats présentés dans le tableau QC-2 révèle que les concentrations maximales des cinq substances qui dépassaient leurs valeurs limites dans la dernière version du modèle de dispersion présentée au MELCCFP ont diminué de 60 % et 95 % avec la mise à jour du modèle. Donc, en modifiant certaines sources d'émissions du projet, telles que décrites au tableau QC-1, il a été possible d'améliorer la dispersion des substances non conformes et de rendre quatre d'entre elles conformes à leur valeur limite.

Toutefois, la concentration maximale prédite pour l'acide nitrique demeure au-dessus de son critère sur 1 heure, et ce, malgré l'application des modifications à certaines sources d'émissions du scénario projet. En comparant les concentrations et niveaux de dépassement de l'acide nitrique du scénario projet (127 %) à celui du scénario préprojet (906 %) présenté aux tableaux D1 et D2 de l'annexe D, il appert que le projet apporte une diminution de la concentration ambiante maximale d'acide nitrique. De plus, le nombre d'heures où le critère est dépassé pour cette substance pour le scénario projet, sur les cinq années de données météo traitées dans le modèle, est de 233. Pour le scénario préprojet, le nombre d'heures de dépassement de la norme est important, et, à ce titre, la 1000e concentration la plus élevée est de 204,5 µg/m^3 comparativement au critère de 86 µg/m^3.

Enfin, la concentration maximale prédite pour l'acide chlorhydrique dans le scénario préprojet est sous la norme sur 4 min (à 50 % de la norme), alors que sa concentration maximale dans la dernière version du modèle de dispersion soumis au MELCCFP elle était à 117 % de la norme. Cette variation est attribuable à la correction du rapport de Bowen dans la présente mise à jour du modèle de dispersion (voir question QC-13).

Sur la base des résultats de la modélisation de la dispersion atmosphérique des substances visées pour les scénarios projet et préprojet, il est possible de conclure que l'exigence de l'article 197 du RAA est satisfaite.

QC-13

Au tableau QC-48.3, l'initiateur calcule une valeur pour le rapport de Bowen de 1 500 pour l'hiver, alors qu'une valeur de 0,5 est attendue. Selon les classifications NLCD (1992 ou 2016), toutes les catégories d'usage au sol ont une valeur de ratio de Bowen de 0,5 pour l'hiver, à l'exception de l'eau libre non gelée qui est de 0,1.

Si la modélisation soumise devait être mise à jour, corriger la valeur de ratio de Bowen en prenant en compte la valeur de 0,5.

Réponse QC-13 :

Le tableau QC-48.3 de notre document de réponses à votre première série de commentaires et questions présente effectivement une valeur erronée du rapport de Bowen pour la période hivernale. Une valeur de 0,5 de rapport de Bowen, pour la période hivernale, a donc été utilisée dans la mise à jour du modèle de dispersion utilisé pour répondre aux plus récentes questions du MELCCFP[5].

QC-14

Au tableau QC-59.2, l'initiateur présente les résultats de la modélisation du NO_2 aux différentes périodes. Toutefois, l'initiateur ne mentionne pas la méthode de conversion du NO en NO_2 qui a été employée pour obtenir ces résultats. La méthode et la justification du choix de cette méthode devront être fournies si la modélisation soumise est mise à jour pour ce contaminant.

Réponse QC-14 :

En se basant sur les lignes directrices du guide du MELCCFP[6], la méthode la plus conservatrice a été utilisée, soit la conversion complète du NO en NO_2. Comme recommandé par le guide, si les concentrations maximales de NO_2 dans l'air ambiant résultant de l'utilisation de cette méthode de conversion, incluant les concentrations initiales, sont sous les normes (pour toutes les périodes), alors la conformité des émissions de NOx est établie.

[5] MELCCFP (2022). *Questions et commentaires pour le projet de valorisation de matières dangereuses résiduelles à l'aide d'un procédé de désorption thermique anaérobie sur le territoire de la municipalité de Contrecœur par Triumvirate Environmental inc.*, Dossier 3211-22-017, 19 octobre 2022.
[6] Couture, Y. (MELCCFP 2008). *Guide d'estimation de la concentration de dioxyde d'azote (NO_2) dans l'air ambiant lors de l'application des modèles de dispersion atmosphérique*.

QC-15

Au tableau QC-59.2, l'initiateur présente les résultats de modélisation sur une période horaire pour sept contaminants sans normes, critères ou seuil d'évaluation préliminaire du risque. Des critères de qualité de l'atmosphère ont été développés pour ces contaminants et sont présentés dans le tableau QC-15.

Tableau QC-15 : critère de qualité de l'atmosphère

CAS	Substance	Période	Critère (µg/m³)	Concentration initiale (µg/m³)	Note
135-98-8	Sec-butylbenzène	1h 1 an	2 750 80	0 0	
95-48-7	o-Crésol	4 min	6	0	
108-39-4	m-Crésol	4 min	1,1	0	
106-44-5	p-Crésol	4 min	0,9	0	
591-35-5	3,5-Dichlorophénol	1 an	1,3	0	Additif avec 120-83-2
103-65-1	n-Propylbenzène	4 min 1 an	19 2,8	0 0	
58-90-2	2,3,4,6-Tétrachlorophénol	1 an	0,01	0	

Les concentrations maximales modélisées dans le domaine d'application des normes et critères doivent être comparées à ces critères. Les résultats ainsi obtenus doivent être discutés. Le cas échéant, des mesures d'atténuation doivent être proposées et leur efficacité doit être démontrée. Pour certains de ces contaminants, la modélisation devrait donc être mise à jour pour correspondre aux périodes pour lesquels les critères ont été développés.

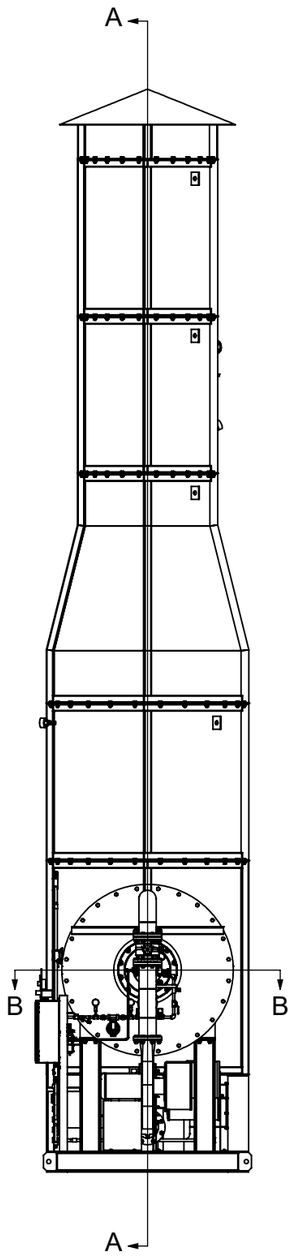
Réponse QC-15 :

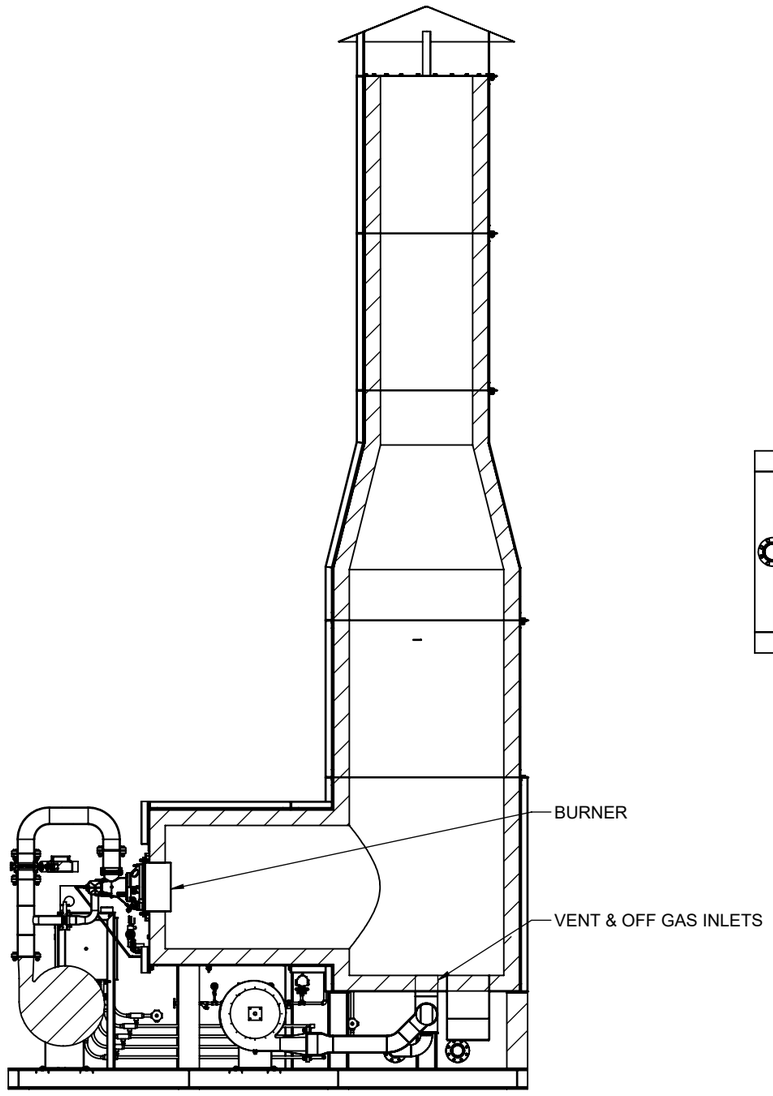
Ces critères ont été considérés dans la mise à jour de l'étude de dispersion atmosphérique pour les scénarios projet et préprojet et sont intégrés dans les tableaux D1 et D2 de l'annexe D présentant les résultats des scénarios modélisés. Aucun de ces critères n'est dépassé, et ce, pour les scénarios préprojet et projet.

Annexe A PLAN DE CONCEPTION DE L'OXYDATEUR THERMIQUE

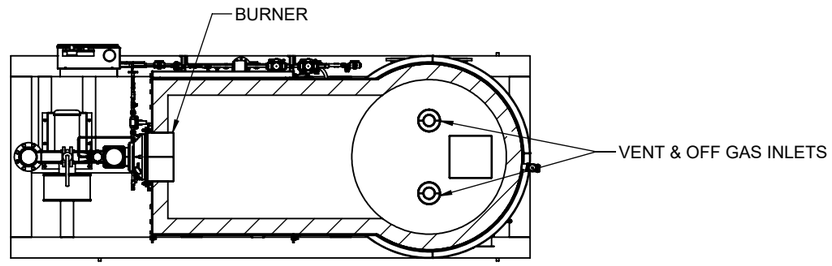
REVISIONS				
REV	DESCRIPTION	DATE	DRAWN BY	APPROVED
A	DRAWING CREATED	11/18/2022	M.DICKINSON	-

NOTES
1. PROJECT: 29 - TRIUMVIRATE
2. NEXT ASSEMBLY: -
3. PID TAG: ME-1601
4. APPROXIMATE WEIGHT: 16150 LBS.
5. REMOVE BURRS, BREAK SHARP EDGES
6. DXF FILE(S) AVAILABLE UPON REQUEST





SECTION A-A
SCALE 1 : 60



SECTION B-B
SCALE 1 : 60

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TOLERANCES
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ANGULAR:
DIMENSIONS ARE IN INCHES

SHEET: 1 OF 1
SHEET SCALE: 1:60
SHEET SIZE: A3
DRAWING NUMBER: 29-TO-00-006
REV: A
APP'D | - | -
DRWN | M.DICKINSON | 11/18/2022
DESCRIPTION: TOU BURNER & GAS INLET LOC DETAIL

REV C

Annexe B DOCUMENTS DE RÉFÉRENCE SUR LA GÉNÉRATION DE NOX PAR LA COMBUSTION

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Conference Paper *in* Journal of Engineering for Gas Turbines and Power · December 2011

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Proceedings of ASME Turbo Expo 2011
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EXPERIMENTAL AND NUMERICAL STUDY OF NO_X FORMATION FROM THE LEAN PREMIXED COMBUSTION OF CH_4 MIXED WITH CO_2 AND N_2

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ABSTRACT

This paper describes an experimental and numerical study of the emission of nitrogen oxides (NO_X) from the lean premixed combustion of gaseous fuels alternative to typical pipeline natural gas in a high intensity, single-jet stirred reactor (JSR). In this study, CH_4 is mixed with varying levels CO_2 and N_2. NO_X measurements are taken at a nominal combustion temperature of 1800 K, atmospheric pressure, and a reactor residence time of 3 ms. The experimental results show the following trends for NO_X emissions as a function of fuel type: 1.) the addition of diluent at constant air flow produces more NO_X per kg of CH_4 consumed, and 2.) N_2 is more effective than CO_2 in increasing the NO_X emission index. Chemical kinetic modelling suggests that this is due to both a decrease in N_2 concentration and the ability of CO_2 to deplete the radicals taking part in NO_X formation chemistry for the mixture diluted with CO_2.

In order to gain insight on flame structure within the JSR, three dimensional computational fluid dynamic (CFD) simulations are carried out for LPM CH_4 combustion. A global CH_4 combustion mechanism is used to model the chemistry. While it does not predict intermediate radicals, it does predict CH_4 and CO oxidation quite well. The CFD model illustrates the flow-field, temperature variation, and flame structure within the JSR. A 3-element chemical reactor network (CRN) including detailed chemistry, is constructed using insight from detailed spatial measurements of the reactor, the results of CFD simulations, and classical fluid dynamic correlations. The experimental and modeling results are in good agreement with GRI 3.0 used in the CRN to model the NO_X emissions for all fuel blends, and they suggest the underlying chemical kinetic reasons for the trends.

1 Introduction

Lean-premixed (LPM) combustion technology is utilized in state of the art gas turbines to provide extremely efficient power generation with low emissions. Traditionally, natural gas has been used almost exclusively in LPM combustion technology. While extensive research on natural gas-fueled LPM combustion has been reported, much less research has been conducted on the use of alternatives to natural gas for LPM combustion devices. In the future, gas turbines will be run with a variety of fuel compositions ranging from syngases with high H_2 content to landfill and digester gas, which are mainly composed of CH_4, CO_2, and N_2. Alternative fuel blends will have a wide range of heating values,

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flame speeds, and chemical composition. It is important to study the behavior of these fuels under LPM conditions to maximize performance efficiency, while minimizing the overall emissions.

The use of landfill gas in LPM combustion systems is of interest for the future of gas turbines. Landfill gas is the product of the decomposition of municipal waste from landfills and waste-water treatment plants. Its composition varies depending on the feedstock; however, it is primarily composed of CH_4 and CO_2 with up to 15% N_2 and other trace compounds [1]. Qin et al. found that the addition of CO_2 to a LPM CH_4 flame increases the total NO_X emissions per mass of CH_4 consumed [2]. Other researchers report that adding more diluent to CH_4 decreases NO_X emissions when reported on a corrected O_2 basis [3], [4]. Although McDonnel et al. report that NO_X emissions decrease with the addition of diluent, they also found that the use of N_2 instead of CO_2 as a diluent resulted in higher NO_X emissions [3], which is consistent with previous work [5]. Flores et al. have shown that NO_X emissions are affected by fuel distribution, stoichiometry, and the chemical composition of the fuel [6]. The present work seeks to extend this statement by exploring how NO_X emissions are also influenced by the experimental setup (combustor geometry, experimental methods) and the method in which the data are reported.

The main objective of this study is to evaluate NO_X formation as a function of CO_2 or N_2 dilution in LPM, constant temperature CH_4 combustion. Constant temperature experiments allow one to explore the influence of chemistry, while removing temperature as a variable. All of the experiments are conducted in a high intensity, single-jet, stirred reactor (JSR). The JSR has two distinct reaction zones much like the gas turbine combustor: a turbulent flame zone that is positioned right around the jet, followed by a post flame zone characterized by super-equilibrium free radical concentrations. Previous studies have shown that NO_X data taken from the JSR are comparable to data taken from actual gas turbine combustors operating at the same pressure and temperature [7]. Thus, the JSR is a useful experimental tool for performing kinetic studies on fuel mixtures that could be burned in a gas turbine.

First the experimental setup is briefly explained, followed by a presentation of the experimental results. The results of three dimensional CFD simulations are presented, which give insight to the flowfield, temperature distribution, and chemical composition of the reactor operating on CH_4. With the aid of the CFD results, a chemical reactor network is developed for the JSR. Its construction and layout are outlined and the model results are compared to experimental data.

2 Experimental Setup

All of the experimental data are obtained from a high intensity, backmixed, single-jet, stirred reactor as shown in Figure 1. Both fuel and air enter the reactor through the premixer. The

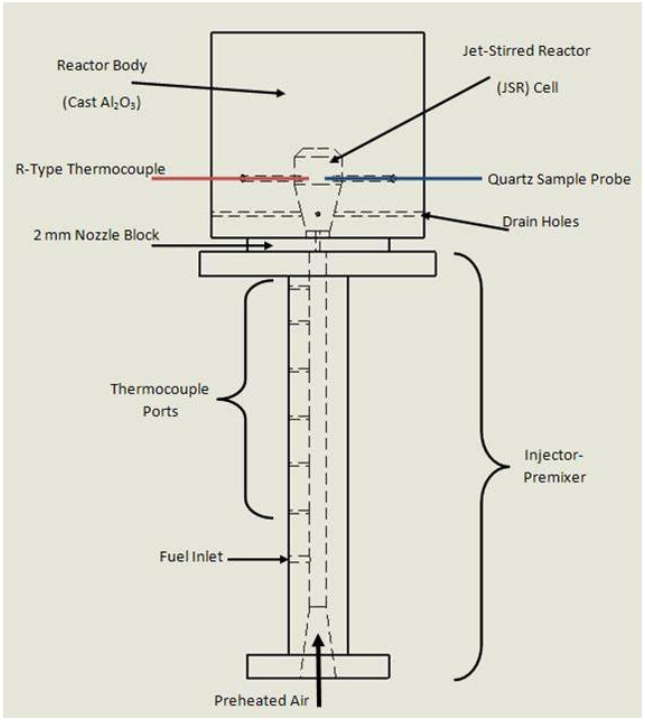

Figure 1: Diagram of Experimental Setup

air is is preheated to 573 K. Once the fuel stream is mixed with the air, the mixture has a nominal temperature of about 550 K as it enters the reactor cavity. The stagnation pressure of the premixed fuel/air mixture is measured 5 cm upstream of the reactor cavity. The premixed reactants enter the cast alumina reactor cavity through a 2mm nozzle resulting in a sonic jet velocity of approximately 450 m/s. The total volume of the reactor is a 15.8 cc, the mass flow rate of air is 1.08E-3 kg/s, and nominal combustion temperature is held constant at 1800 K. This results in a mean fluid residence time of 2.7 ± 0.2 ms.

As shown in Figure 2, both temperature and species concentrations are measured at 2/3 of the reactor height with the nominal sampling location being 2 mm inside the reactor wall. This sampling location is far enough into the reactor to avoid thermal and fluid boundary layer effects, but not so far as to experience the effects of the jet. In addition to collecting data at the standard sampling location, detailed reactor spatial probing is conducted in order to gain insight of flame structure within the reactor. Both temperature and species measurements are taken radially between the reactor wall and centerline at 2/3 of the total reactor height.

The combustion gas temperature is measured with a type R thermocouple that is coated with alumina to prevent catalytic effects. The measured combustion temperature is between 50 and 70 K below the reported temperature which has been corrected for both radiation to the colder reactor wall and conduction through the wire [8]. The hot combustion gases are sampled

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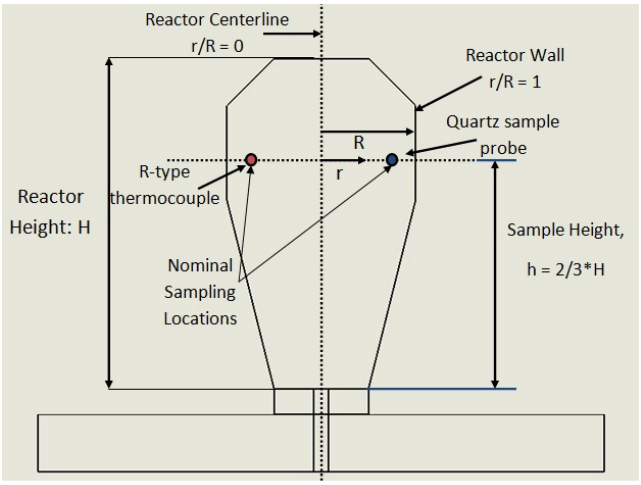

Figure 2: Sampling locations within the JSR

through a warm water cooled, quartz sample probe. The sample gas is drawn by a metal bellows pump into a heated teflon tube (to prevent condensation). The sample is then drawn through an ice bath where the H_2O in the sample is removed and the dried gas is sent to a three gas (CO_2, CO, and O_2) analyzer and a NO_X analyzer in parallel. The CO_2 and CO analyzers operate on the NDIR principle, while the O_2 and NO_X analyzers are paramagnetic and chemiluminescent instruments, respectively.

3 Experimental Results

Since the experiments focus on the influence of the diluents on NO_X, we designed the experiments to hold the temperature constant for all diluent concentrations (N_2 versus CO_2). We achieve this as follows. First, the air flow is held constant. The CH_4 flow is selected to achieve a constant temperature of 1800 K in the recirculation zone. As the diluent loading is increased, the natural tendency of the reactor to run cooler is balanced by increasing the CH_4 flow rate. Thus, as the diluent is increased, the CH_4 flow rate is also increased, and the overall fuel/oxidant ratio approaches stoichiometric.

An important question is how to best present the NO_X data. In the present experiments (1) the stoichiometry varies, and (2) the CO_2 and N_2 dilute the flow. NO_X mole fraction (as ppm) is the normal way to present the emission data. The mole fraction is, however, influenced by dilution effects, in this case both due to stoichiometry and dilution. In other words, ppm values for NO_X can change due to differences in stoichiometry or dilution. While the stoichiometry effect can be handled by correcting to a common O_2 value, the presence of the diluents can change mole fraction without any change in chemistry. We thus conclude that the most meaningful way to present the data is as a NO_X emission index, i.e., the amount of NO_X formation attributed to each CH_4 molecule entering the reactor. This avoids mole fraction changes that are due only to dilution (via variable stoichiometry or CO_2 versus N_2).

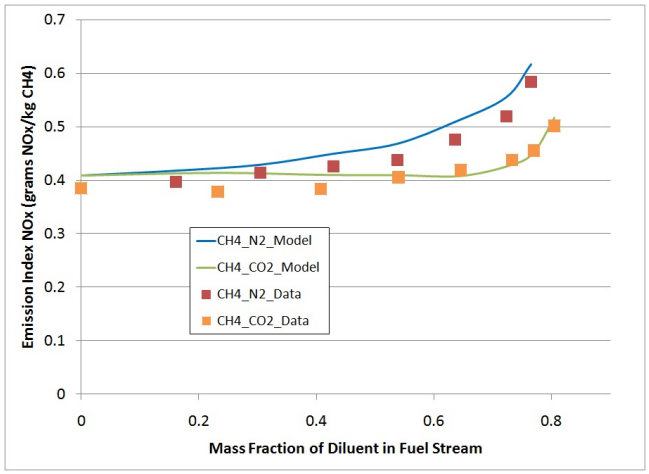

Figure 3: Measured NO_X as EI versus mass fraction of N_2 or CO_2 diluent in fuel stream. Temperature is maintained constant at 1800 K

Figure 3 shows that the NO_X emission index (grams NO_X/kg CH_4) increases for both N_2 and CO_2 dilution. The results also show that dilution with N_2 is more effective at enhancing NO_X formation than CO_2 dilution. There are, however, several ways to correlate the effect of the diluents, e.g., plotting against mass fraction of diluent, mole fraction of diluent, etc. As mentioned above, increasing the diluent flow requires an increase in CH_4 flow to maintain the 1800 K reactor temperature. This means that the mixture approaches a stoichiometric fuel-air ratio and the O_2 concentration decreases. In examining the various ways to correlate the effect of the diluents on NO_X formation, we concluded that plotting against O_2 concentration was the most fundamental approach, because the relationship between fuel, O_2, and NO_X is at the core of the chemical behavior.

Figure 4 shows the NO_X emissions index plotted against the O_2 concentration in the exhaust. As in Figure 3, the fuel stream diluted with N_2 is more effective at producing NO_X emissions than with CO_2 dilution when compared on a common O_2 basis. Thus, there is evidence to suggest that there may be a chemical kinetic explanation for this phenomenon.

For reference, the measured NO_X is displayed versus exhaust O_2 concentration in Figure 5. Note that there is some difference between Figures 4 and 5. In general, the specific heat of the two additives on a mass basis is sufficiently similar that (1) the tendency of the reactor to cool upon additive addition is nearly the same for the two, and (2) the increase in CH_4 flow needed to maintain the 1800 K flame temperature is similar between the two. Thus, in this case the mole fraction results and the emission index results report similar trends. The other effect that make the data appear different on an emission index is due to the

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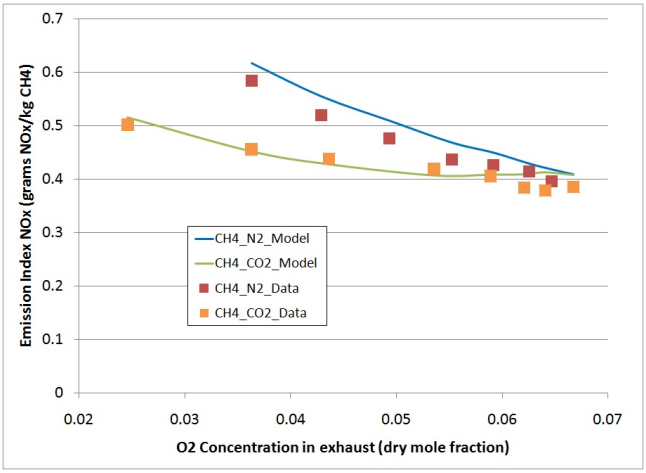

Figure 4: Measured NO_X as EI versus exit gas O_2 (mole %, dry). Temperature is maintained constant at 1800 K

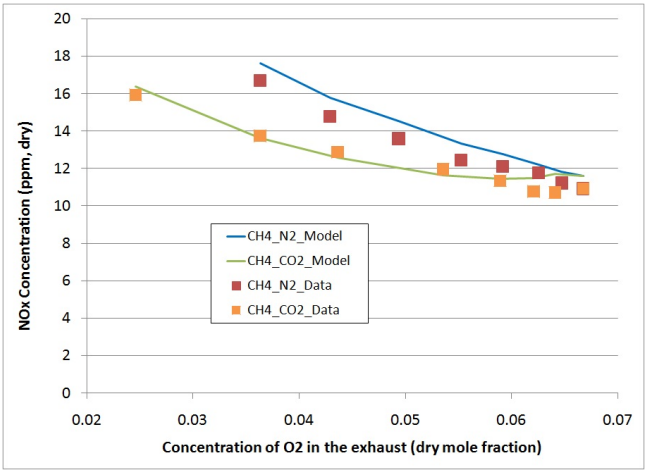

Figure 5: Measured NO_X as (ppm, dry) versus exit gas O_2 (mole %, dry). Temperature is maintained constant at 1800 K

increasingly larger molecular weight in the product gas as more CO_2 is added. For N_2 dilution, the molecular weight remains essentially constant throughout the entire range of experiments. As shown in Figures 3 through 5, the model predicts the data quite well. The modelling results are discussed in more depth in Section 6.

4 CFD Modelling

Three dimensional CFD simulations are carried out with pure CH_4 premixed with air. The simulations are conducted with a domain of about 1,000,000 cells encompassing both the solid and fluid portion of the JSR. Due to the heavily swirling nature of the flow, both the standard [9] and realizable [10] k-ε models were unable to obtain convergence. Thus, the 9 equation Reynolds stress model [11] is employed due to its inherent ability to handle the highly swirling nature of the flow inside the JSR. The flow though the nozzle inlet is highly compressible; thus, density in the reactor is modelled using the ideal gas equation. A multidimensional heat transfer model is utilized that accounts for convection on both the outer and inner surfaces of the JSR, conduction within the entire domain, and radiation on both the inner and outer surface of the JSR. The radiation on the inner surface is modelled using the Discrete Ordinates Model [12], while the radiation on the outer surface is modelled as a simple black body with a view factor equal to unity. The partial differential equations that govern both flow and heat transfer within the JSR are solved using the ANSYS Fluent software package [13].

The chemistry within the reactor is modelled with the finite rate/eddy-dissipation model [14]. In this model, the reaction rate is computed by both an Arrhenius expression and an expression that incorporates turbulent effects. The turbulent mixing, or eddy-dissipation reaction rate is governed by the the large eddy mixing time scale: k/ε, while the chemical rate is generally governed by one or two global Arrhenius steps [13]. The net reaction rate is computed as the smaller of the two rates. Global CH_4 oxidation rates for atmospheric combustion from Nicol are used in the simulation [15]. The global chemistry does a reasonably good job of predicting CH_4 and CO oxidation as shown in Figures 6 and 7.

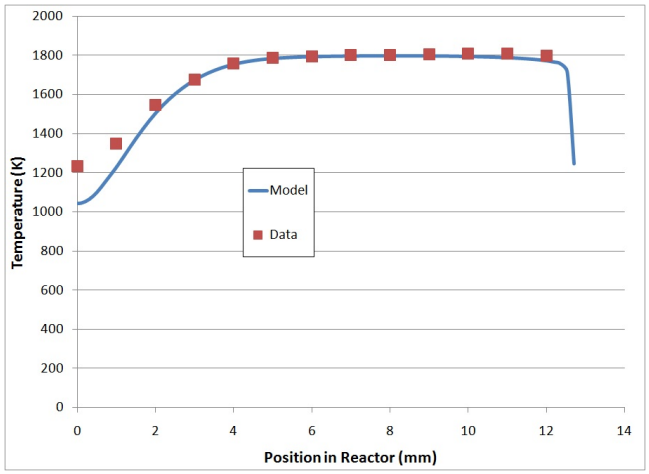

Figure 6: Profile of temperature from reactor centerline to wall, measured and predicted by CFD for CH_4 combustion (w/o diluents) for exit gas O_2 of 6.6% (mole %, dry)

The contours of temperature and CO concentration are shown in Figure 8. This figure illustrates the two zone combustion behavior mentioned above. The highly turbulent flame zone is anchored around the nozzle, which is outlined by the region of high CO concentration. This flame zone is then followed by a super-equilibrium post flame recirculation zone, where the radicals (indicated by CO concentration) are starting to relax and the temperature is fairly uniform. Although, this CFD model does

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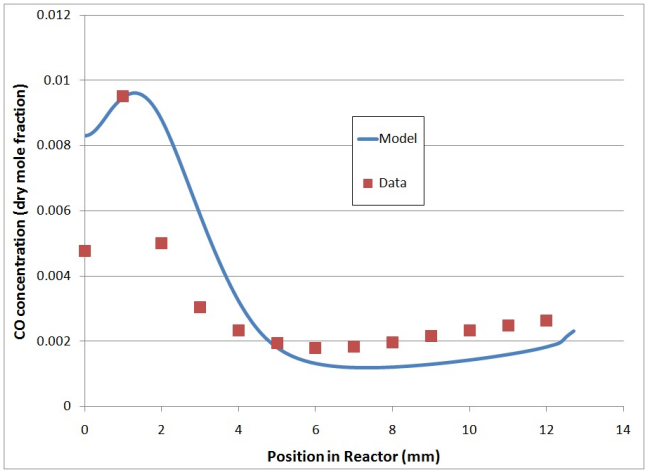

Figure 7: Profile of CO from reactor centerline to wall, measured and predicted by CFD for CH_4 combustion (w/o diluents) for exit gas O_2 of 6.6% (mole %, dry)

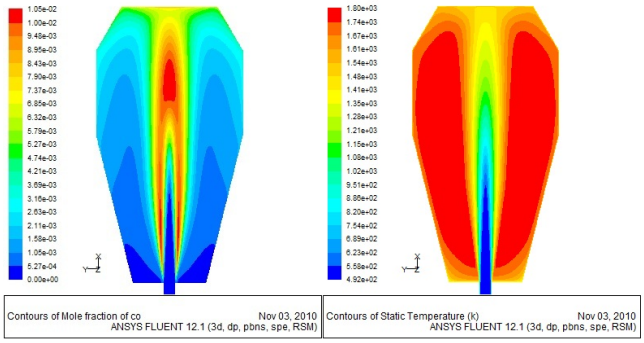

Figure 8: CO and temperature contours by CFD for JSR fired on CH_4 (w/o diluents) for exit gas O_2 of 6.6% (mole %, dry)

not predict intermediate radicals and NO_X, the CO contours and flow field can be used as guidelines to develop a chemical reactor network (CRN), which can incorporate detailed chemistry.

5 Development of the CRN

The CFD model is used as a basis to construct a chemical reactor network composed of perfectly stirred reactors (PSR) as shown in Figure 9. The first element, PSR 1, represents the turbulent flame brush that does not see any entrainment from the recirculation zone. It is modelled as a PSR at blowout, which is an adiabatic PSR that is 1% larger than the smallest volume that will sustain combustion with the given inlet conditions. From the CFD model, it is found that approximately 90% of the flow leaving the jet passes through this reactor. About 10% of the flow proceeds through the side of the jet and mixes with hot gases coming from the recirculation zone. Denoted as PSR 3, or shear zone, this reactor is representative of a turbulent premixed strained flame, where cold reactants strain against hot recirculated products. PSR 3 is also adiabatic since it does not come

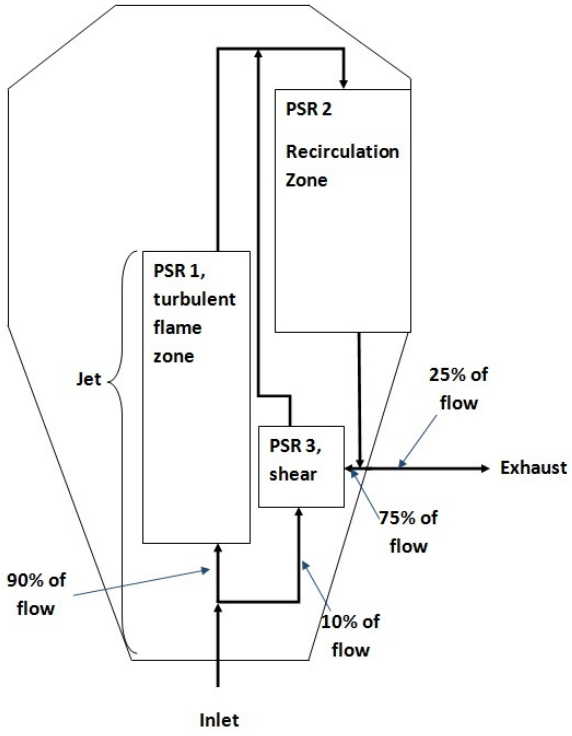

Figure 9: Chemical Reactor Network constructed with from the calculated flow field within the CFD model

into contact with the outside wall. Its volume is estimated to be about half of the volume computed for PSR 1 from the CFD simulation. The contents of both PSR 1 and PSR 3 continue into PSR 2, which represents the super-equilibrium recirculation zone within the JSR. PSR 2 is assigned the remaining reactor volume (most of the JSR volume) and is run at a non-adiabatic temperature of 1800 K. The CFD model is again consulted to choose the flow fraction that is being exhausted rather than sent back to the recirculation zone. At several axial locations along the height of the reactor the downward mass flow is integrated. By subtracting this value from the known mass flow leaving the reactor (mass conservation), one obtains an estimate for the mass flow that is returning to the recirculation zone through PSR 3. It is found that approximately 75% of the flow returns to the recirculation zone, while 25% is exhausted. This flow fraction is verified by using the particle tracking feature within the software [13].

6 CRN Modelling Results and Discussion

For all of the modelling reported here, the 52 species, 323 reaction GRI 3.0 mechanism is utilized [16]. As shown in Figures 3 through 5, the model predicts the experimental NO_X data quite well.

These results raise two main questions: 1.) Why do NO_X emissions go up when the O_2 in the exhaust decreases/mass fraction of diluent increases? and 2.) Why are NO_X emissions higher

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for fuels diluted with N_2 rather than CO_2?

In order to gain a better insight on these trends, each of the four NO_X production pathways is isolated and the model is re-run. The four pathways to NO_X formation are Zeldovich [17], N_2O [18], NNH [19], and prompt [20], and the contributions of each as a function of dilution are shown in Figures 10 and 11. Figure 12 shows the pathway contribution within each reactor of the CRN at a common O_2 concentration of 3.6% dry mole fraction in the exhaust. Here the emission index from each of the reactors is normalized by reactor volume and residence time.

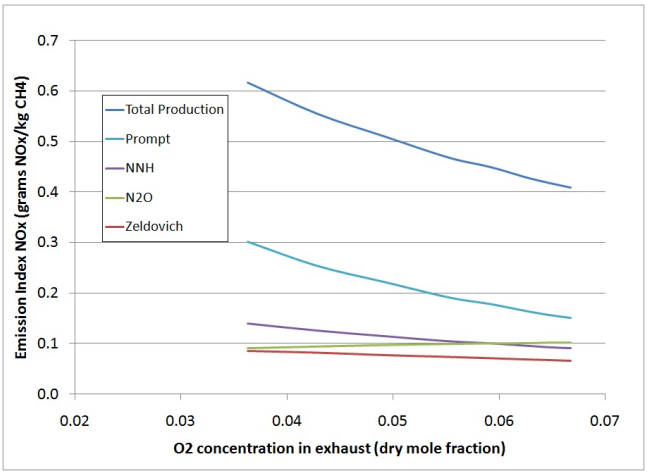

Figure 10: NO_X emission index predicted by CRN model: total and by four pathways. CH_4 diluted with N_2

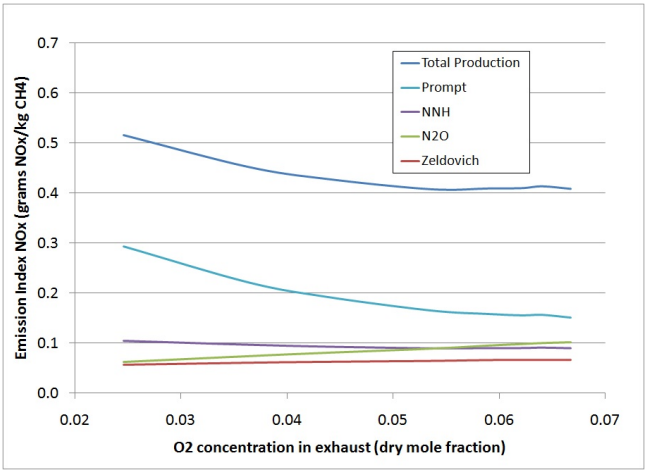

Figure 11: NO_X emission index predicted by CRN model: total and by four pathways. CH_4 diluted with CO_2

There are a couple points worth noting. Due to the small volume and extremely short residence time of the shear reactor (it has approximately three times more mass flow than the

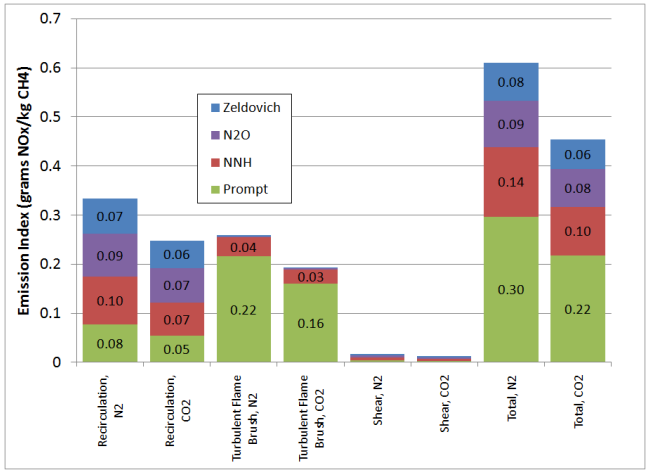

Figure 12: NO_X production reported as emission index for each of the four mechanisms in each of the three reactor elements of the CRN model. O_2 concentration is 3.6% (dry mole fraction)

flame brush), it is essentially a mixing element and can be ignored when discussing chemical effects. Thus, attention can be focussed on the flame brush and recirculation zone. Analysis of Figures 10, 11, and 12 show the following trends for NO_X formation in the JSR:

1. Prompt NO_X is the major source of NO_X for this experiment, and all three figures support this.
   (a) This may be related to the relatively high CH_4-air equivalence ratios used: 0.71-0.86 for N_2 dilution and 0.71-0.92 for CO_2 dilution. Note that for most LPM combustion devices operating on CH_4, the equivalence ratio ranges from 0.45 to 0.65.
   (b) The prompt NO_X increases as the dilution level is increased (ie. as the exit gas O_2 decreases). This is expected because of the increasing amounts of CH_4 required as the dilution levels are increased.
   (c) Much of the prompt NO_X is formed in the turbulent flame brush (ie. flame zone) modelled as an adiabatic PSR operating near blowout condition.
2. NNH contributes a relatively small amount of NO_X and the N_2O and Zeldovich sources of NO_X are negligible within the flame brush as shown in Figure 12, because of this reactor's short residence and low temperature. The computed temperature within the flame brush ranges between 1609 and 1612 K for both diluted fuels at all dilution levels.
3. All four sources of NO_X contribute in the recirculation zone, modelled as a PSR at measured temperature (1800K).
4. The sources of NO_X are greater for N_2 dilution than for CO_2 dilution in both the turbulent flame brush and the recirculation zone.

These NO_X trends are supported by the concentrations of free radicals O, H, and CH shown in Figures 13, 14, and 15, as

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calculated from the CRN modelling.

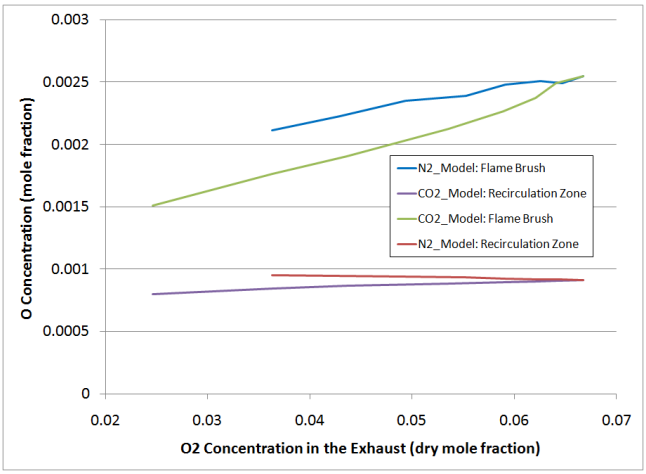

Figure 13: O atom concentration in the recirculation zone and PSB for both diluted fuels

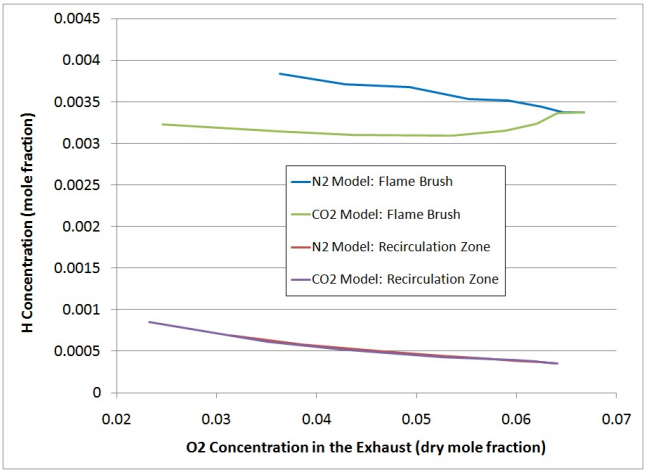

Figure 14: H-atom concentration in the recirculation zone and turbulent flame brush for both diluted fuels

When compared to no dilution, the N_2 mole fraction is 5% greater for maximum N_2 dilution and 17% smaller for maximum CO_2 dilution. For small concentrations of NO_X at constant temperature (which is the case here) Zeldovich NO_X forms in proportion to $[N_2][O]$, where [ ] means moles/vol. Looking at the recirculation zone, for increasing N_2 dilution, O is nearly constant and N_2 increases; thus, Zeldovich NO_X increases with dilution. However, for increasing CO_2 dilution, mole fractions of both O and N_2 decrease: thus, Zeldovich NO_X decreases with dilution.

Nitrous oxide (N_2O) is depleted by reaction with both O and H; however, in this pathway NO is only formed directly through reaction with O. As shown above in Figure 12 most of the NO_X formed through the N_2O pathway is formed in the recirculation zone. Figure 14 shows H-atom increasing as the dilution level of the JSR increases. This trend is the same for both N_2 and CO_2 dilution. Shown in Figure 13, the O concentration in the recirculation zone falls slightly for CO_2 dilution and stays flat for dilution with N_2. Due to both of these effects, the contribution to NO production from N_2O falls for both diluents as dilution increases; slightly more for CO_2 dilution than N_2.

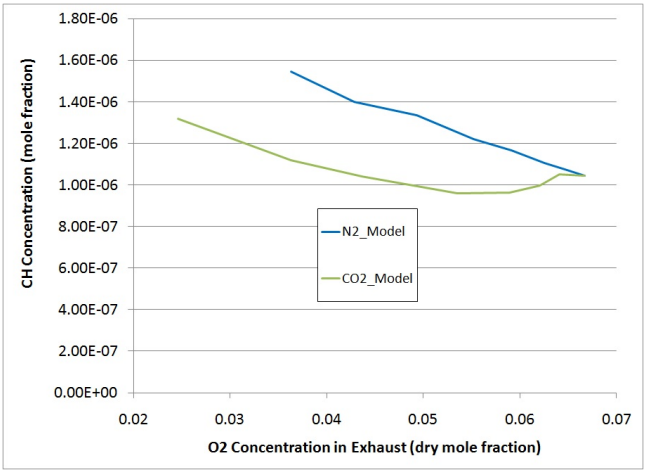

Figure 15: CH concentration within the Flame Brush for CH_4 diluted with both N_2 and CO_2

As seen in Figures 10 and 11, NO formed from NNH increases as the N_2 and CO_2 dilution levels increase. As noted from Figure 12, it forms in both reactor zones. NNH is formed by reaction of N_2 with H, and NO is formed by reaction of NNH with O. NNH concentration follows the upward trend shown for H-atom in Figure 14, tempered by increasing N_2 concentration for N_2 dilution and decreasing N_2 concentration for CO_2 dilution. The result is a somewhat greater increase in NO with dilution level for N_2 than for CO_2.

Prompt NO forms as CH radical reacts with N_2 to form HCN and N, both of which oxidize to NO. CH has a short lifetime; thus, the prompt NO is produced more significantly in the flame brush than in the recirculation zone. The flame brush concentrations of CH are plotted in Figure 15, where they are seen to increase significantly as more N_2 and CH_4 are added to the reactor. Small amounts of CO_2 dilution appear to suppress CH, though as more CO_2 is added, the CH increases.

7 Conclusions

A recirculation-stabilized combustor is used to generate NO_X emission data for LPM CH_4/air combustion diluted with either N_2 or CO_2. This experiment is designed to simulate the combustion of landfill gas. The experiments are conducted at a constant reactor temperature and residence time. NO_X emissions (expressed in terms of CH_4 emissions index) increase with di-

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lution, and dilution with N_2 yields higher NO_X emissions than dilution with CO_2. To explain these results, a chemical reactor network, CRN, is developed using insight from a three dimensional CFD simulation with simplified chemistry. This CRN with the full GRI 3.0 mechanism is shown to effectively model the experimental data collected.

The CRN model indicates that the increase in NO_X emissions with increased dilution is due to an enhancement of the prompt NO_X pathway resulting from an increase in the CH radical concentration as the mixture moves towards stoichiometric. The model also suggests that both a smaller N_2 concentration and a preferential loss of free radicals for dilution with CO_2, results in decreased NO_X emissions for CO_2 dilution vs. N_2 dilution.

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TECHNICAL BULLETIN

NITROGEN OXIDES (NOx), WHY AND HOW THEY ARE CONTROLLED

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November 1999

Nitrogen Oxides (NOx), Why and How They Are Controlled

Prepared by

Clean Air Technology Center (MD-12)
Information Transfer and Program Integration Division
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
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CORRECTION NOTICE

This document, EPA-456/F-99-006**a**, corrects errors found in the original document, EPA-456/F-99-006. These corrections are:

Page 8, fourth paragraph: "Destruction or Recovery Efficiency" has been changed to "Destruction or Removal Efficiency;"

Page 10, Method 2. Reducing Residence Time: This section has been rewritten to correct for an ambiguity in the original text.

Page 20, Table 4. Added Selective Non-Catalytic Reduction (SNCR) to the table and added acronyms for other technologies.

Page 29, last paragraph: This paragraph has been rewritten to correct an error in stating the configuration of a typical cogeneration facility.

Page30, Internal Combustion Reciprocating Engines: A sentence has been added to the end of this section to refer the readers to Table 13 for more information;

Page 41, third through seventh paragraphs: These paragraphs were renumbered to correct for a numbering error (numbers 6 and 7 were used twice).

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Nitrogen Oxides (NOx), Why and How They Are Controlled

When we try to look only at one thing in Nature,
we find it connected to everything else.
John Muir

Nitrogen oxides (NOx) are a very interesting and important family of air polluting chemical compounds. This bulletin explains why NOx are important air pollutants and how NOx are formed and react in the atmosphere. This bulletin also discusses the principles on which all NOx control and pollution prevention technologies are based; available NOx technologies for various combustion sources; and performance and cost of NOx technologies..

WHY SHOULD WE CONTROL NOx?

NOx represent a family of seven compounds. Actually, EPA regulates only nitrogen dioxide (NO_2) as a surrogate for this family of compounds because it is the most prevalent form of NOx in the atmosphere that is generated by anthropogenic (human) activities. NO_2 is not only an important air pollutant by itself, but also reacts in the atmosphere to form ozone (O_3) and acid rain. It is important to note that the ozone that we want to minimize is tropospheric ozone; that is, ozone in the ambient air that we breathe. We are not talking about stratospheric ozone in the upper atmosphere that we cannot breathe. Stratospheric ozone protects us and the troposphere from ionizing radiation coming from the sun.

EPA has established National Ambient Air Quality Standards (NAAQS) for NO_2 and tropospheric ozone. The NAAQS define levels of air quality that are necessary, with a reasonable margin of safety, to protect public health (primary standard) and public welfare (secondary standard) from any known or anticipated adverse effects of pollution. The primary and secondary standard for NO_2 is 0.053 parts per million (ppm) (100 micrograms per cubic meter), annual arithmetic mean concentration.

Tropospheric ozone has been and continues to be a significant air pollution problem in the United States and is the primary constituent of smog. Large portions of the country do not meet the ozone NAAQS and thereby expose large segments of the population to unhealthy levels of ozone in the air. NO_2 reacts in the presence of air and ultraviolet light (UV) in sunlight to form ozone and nitric oxide (NO). The NO then reacts with free radicals in the atmosphere, which are also created by the UV acting on volatile organic compounds (VOC). The free radicals then recycle NO to NO_2. In this way, each molecule of NO can produce ozone multiple times.[40] This will continue until the VOC are reduced to short chains of carbon compounds that cease to be photo reactive (a reaction caused by light). A VOC molecule can usually do this about 5 times.

In addition to the NO_2 and Ozone NAAQS concerns, NOx and sulfur oxides (SOx) in the

atmosphere are captured by moisture to form acid rain. Acid rain, along with cloud and dry deposition, severely affects certain ecosystems and directly affects some segments of our economy. All of these facts indicate an obvious need to reduce NOx emissions. However, to successfully do so, we must understand the generation and control of the NOx family of air pollutants.

WHAT IS A NITROGEN OXIDE?

Diatomic molecular nitrogen (N_2) is a relatively inert gas that makes up about 80% of the air we breathe. However, the chemical element nitrogen (N), as a single atom, can be reactive and have ionization levels (referred to as valence states) from plus one to plus five. Thus nitrogen can form several different oxides. Using the Niels Bohr model of the atom, valence state relates to the number of electrons which are either deficient (positive valence) or surplus (negative valence) in the ion when compared with the neutral molecule. The family of NOx compounds and their properties are listed in Table 1.

Table 1. Nitrogen Oxides (NOx)

Formula	Name	Nitrogen Valence	Properties
N_2O	nitrous oxide	1	colorless gas water soluble
NO N_2O_2	nitric oxide dinitrogen dioxide	2	colorless gas slightly water soluble
N_2O_3	dinitrogen trioxide	3	black solid water soluble, decomposes in water
NO_2 N_2O_4	nitrogen dioxide dinitrogen tetroxide	4	red-brown gas very water soluble, decomposes in water
N_2O_5	dinitrogen pentoxide	5	white solid very water soluble, decomposes in water

Oxygen ions are always at valence minus 2. Depending upon the number of oxygen ions (always balanced by the valence state of nitrogen), NOx can react to either deplete or enhance ozone concentrations. The nitrogen ion in these oxides really does a dance in which it has (at different times) various numbers of oxygen ions as partners. Nitrogen changes its number of partners when it changes its ionization energy level. This happens whenever NOx: (1) is hit with a photon of ionizing radiation (UV or a shorter wavelength light); (2) is hit with enough photons that together transfer enough energy to change its ionization level; (3) is catalyzed; (4) is stimulated sufficiently by thermal (IR) energy; (5) reacts with a chemically oxidizing or reducing radical (an ionized fragment of a molecule); or (6) reacts with a chemically oxidizing or reducing

ion (an atom with unbalanced electrical charge).

When any of these oxides dissolve in water and decompose, they form nitric acid (HNO_3) or nitrous acid (HNO_2). Nitric acid forms nitrate salts when it is neutralized. Nitrous acid forms nitrite salts. Thus, NOx and its derivatives exist and react either as gases in the air, as acids in droplets of water, or as a salt. These gases, acid gases and salts together contribute to pollution effects that have been observed and attributed to acid rain.

Nitrous oxide (N_2O), NO, and NO_2 are the most abundant nitrogen oxides in the air. N_2O (also known as laughing gas) is produced abundantly by biogenic sources such as plants and yeasts. It is only mildly reactive, and is an analgesic (i.e., unlike an anaesthetic you still feel pain, but you feel so good that you just don't mind it). N_2O is an ozone depleting substance which reacts with O_3 in both the troposphere (i.e., below 10,000 feet above sea level) and in the stratosphere (50,000 - 150,000 feet). N_2O has a long half-life, estimated at from 100 to 150 years.

Oxidation of N_2O by O_3 can occur at any temperature and yields both molecular oxygen (O_2) and either NO or two NO molecules joined together as its dimer, dinitrogen dioxide (N_2O_2). The NO or N_2O_2 then oxidizes quickly (in about two hours) to NO_2. The NO_2 then creates an ozone molecule out of a molecule of oxygen (O_2) when it gets hit by a photon of ionizing radiation from sunlight. N_2O is also a "Greenhouse Gas" which, like carbon dioxide (CO_2), absorbs long wavelength infrared radiation to hold heat radiating from Earth, and thereby contributes to global warming.

Emissions of NOx from combustion are primarily in the form of NO. According to the Zeldovich equations, NO is generated to the limit of available oxygen (about 200,000 ppm) in air at temperatures above 1,300°C (2,370°F). At temperatures below 760°C (1,400°F), NO is either generated in much lower concentrations or not at all. Combustion NO is generated as a function of air to fuel ratio and is more pronounced when the mixture is on the fuel-lean side of the stoichiometric ratio[50] (the ratio of chemicals which enter into reaction). The Zeldovich equations are:

$$N_2 + O - NO + N$$
$$N + O_2 - NO + O$$
$$N + OH - NO + H$$

Except for NO from soils, lightning and natural fires, NO is largely anthropogenic (i.e., generated by human activity). Biogenic sources are generally thought to account for less than 10% of total NO emissions. NO produces the same failure to absorb oxygen into the blood as carbon monoxide (CO). However, since NO is only slightly soluble in water, it poses no real threat except to infants and very sensitive individuals.

NO_2 is present in the atmosphere and in acid rain. It produces nitric acid (HNO_3) when dissolved in water. When NO_2 reacts with a photon to make O_2 become O_3, NO_2 becomes NO. This NO is then oxidized within hours to NO_2 by radicals from the photo reaction of VOC. Therefore, our

present ozone concentration is the product of both NOx and VOC pollution.

Dinitrogen trioxide (N_2O_3) and dinitrogen tetroxide (N_2O_4) exist in very small concentrations in flue gas. However, they exist in such low concentrations in the atmosphere that both their presence and their effect are often ignored. N_2O_4 is two NO_2 molecules joined together (another dimer) and reacts like NO_2; so, the presence of N_2O_4 may be masked by the more abundant NO_2.

Dinitrogen pentoxide (N_2O_5) is the most highly ionized form of nitrogen oxide. It is generated in air in a very small concentration, unless it is emitted from a process (such as a nitric acid production facility) that is specifically designed to generate it. N_2O_5 is highly reactive, and forms nitric acid (HNO_3) when it decomposes in water.

Some experts feel that NO_2 is a good surrogate for NOx because NO is rapidly converted to NO_2, and N_2O has such a long life because it is not highly reactive. Others feel that due to their role in forming ozone, both NO and NO_2 should be considered NOx. Still others feel that all nitrogen oxides (including N_2O) need to be regulated. NO and NO_2 are certainly the most plentiful forms of NOx and they are largely (but not exclusively) from anthropogenic sources. N_2O is largely biogenic, and as such is not subject to regulation. For environmental purposes, using the concentration of NO_2 as a surrogate for the concentration of NOx has seemed to suffice, for it is the precursor for ozone.

WHERE DOES NOx COME FROM?

Automobiles and other mobile sources contribute about half of the NOx that is emitted. Electric power plant boilers produce about 40% of the NOx emissions from stationary sources.[34] Additionally, substantial emissions are also added by such anthropogenic sources as industrial boilers, incinerators, gas turbines, reciprocating spark ignition and Diesel engines in stationary sources, iron and steel mills, cement manufacture, glass manufacture, petroleum refineries, and nitric acid manufacture. Biogenic or natural sources of nitrogen oxides include lightning, forest fires, grass fires, trees, bushes, grasses, and yeasts.[1] These various sources produce differing amounts of each oxide. The anthropogenic sources are approximately shown as:

Mobile Sources	Electric Power Plants	Everything Else
50%	20%	30%

This shows a graphic portrayal of the emissions of our two greatest sources of NOx. If we could reduce the NOx emissions from just these two leading categories, we might be able to live with the rest. However, don't expect either of these categories to become zero in the foreseeable future. We cannot expect the car, truck, bus, and airplane to disappear. The zero-emission car is still on the drawing board and not on the production line. Also, social customs will have to change before consumption of electricity can be reduced.

In all combustion there are three opportunities for NOx formation. They are:

1. Thermal NOx - The concentration of "thermal NOx" is controlled by the nitrogen and oxygen molar concentrations and the temperature of combustion. Combustion at temperatures well below 1,300°C (2,370°F) forms much smaller concentrations of thermal NOx.

2. Fuel NOx - Fuels that contain nitrogen (e.g., coal) create "fuel NOx" that results from oxidation of the already-ionized nitrogen contained in the fuel.

3. Prompt NOx - Prompt NOx is formed from molecular nitrogen in the air combining with fuel in fuel-rich conditions which exist, to some extent, in all combustion. This nitrogen then oxidizes along with the fuel and becomes NOx during combustion, just like fuel NOx. The abundance of prompt NOx is disputed by the various writers of articles and reports - probably because they each are either considering fuels intrinsically containing very large or very small amounts of nitrogen, or are considering burners that are intended to either have or not have fuel-rich regions in the flame.

HOW DOES NOx AFFECT THE ENVIRONMENT?

Because NOx are transparent to most wavelengths of light (although NO_2 has a brownish color and the rare N_2O_3 is black), they allow the vast majority of photons to pass through and, therefore, have a lifetime of at least several days. Because NO_2 is recycled from NO by the photo reaction of VOC to make more ozone, NO_2 seems to have an even longer lifetime and is capable of traveling considerable distances before creating ozone. Weather systems usually travel over the earth's surface and allow the atmospheric effects to move downwind for several hundred miles. This was noted in EPA reports more than twenty years ago. These reports found that each major city on the East coast has a plume of ozone that extends more than a hundred miles out to sea before concentrations drop to 100 parts per billion (ppb). Another report cited the same phenomenon for St. Louis. Therefore, this problem was not just on the sea coast. Since ozone in clean air has a lifetime of only a few hours, this phenomenon is a measure of the effect and the persistence of both VOC and NOx.

Differences in the distance estimates between the emission of NOx and the generation of ozone may be related to differences in plume transport (wind) speeds as well as other meteorological and air quality factors. It is important to note that, under the right conditions, power plant plumes may travel relatively long distances overnight with little loss of VOC, NO and NO_2 . These pollutants can thus be available to participate in photochemical reactions at distant locations on the following day.[41] Figure 1 shows a map of NOx concentration drawn by the Center for Air Pollution Impact and Trend Analysis (CAPITA) at Washington University in St. Louis and reported to the Ozone Transport Assessment Group, a national workgroup that addressed the problem of ground-level ozone (smog) and the long-range transport of air pollution across the Eastern United States. OTAG was a partnership among the EPA, the Environmental Council of the States (ECOS) and various industry and environmental groups with the goal of developing a thoughtful assessment and a consensus agreement for reducing ground-level ozone and the

pollutants that cause it. The animated version of Figure 1 shows the trajectory of NOx emissions moving with the weather over an 8 day period.

Figure 2 is a map of ozone concentration that shows the same trajectory over the 8 day period. The animated version shows concentrations of both NOx and ozone moving with the weather for several hundred miles.[5]

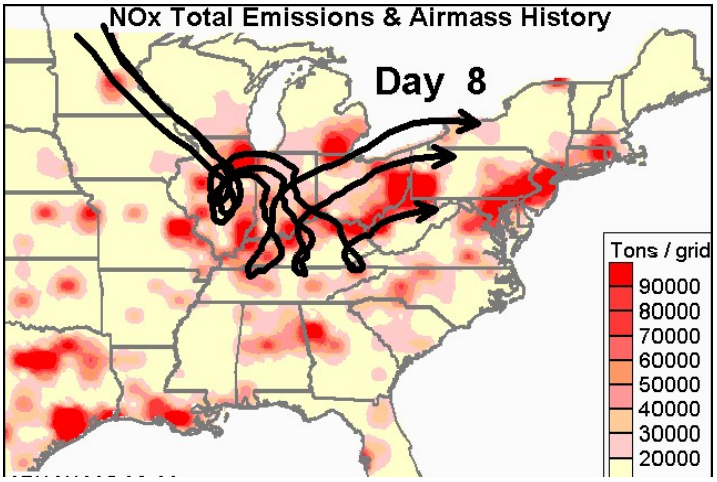

Figure 2 NOx Map

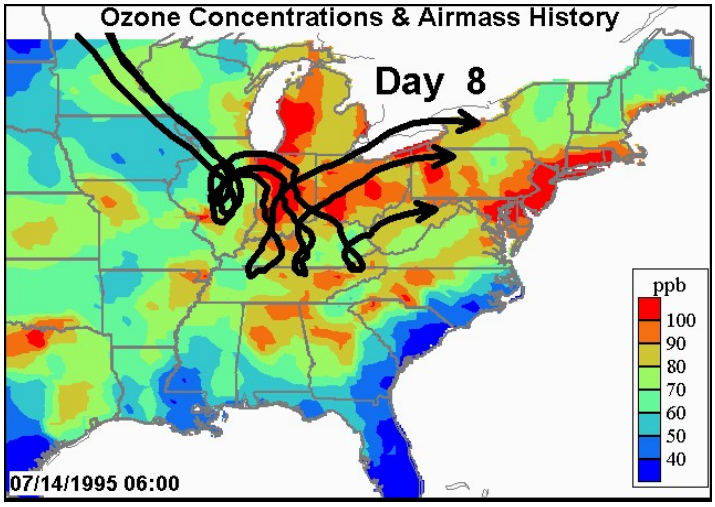

Figure 3 Ozone Map

Ozone is the primary constituent of smog. Between 1970 and 1990, we in the United States have tried to control ozone primarily by controlling the emissions of VOC. However, we have had mixed results, for although some areas reduced their VOC emissions and attained their ozone goals, others have not. It now appears that the communities that failed to meet their ozone goals

may not be completely at fault, for they appear to be affected by NOx and VOC emissions in the air coming to them. To meet the ozone NAAQS, EPA must now regulate emissions of NOx regionally.

ARE THERE OTHER NOx RELATED ISSUES?

Yes. Nutrient enrichment problems (eutrophication) occur in bodies of water when the availability of either nitrates or phosphates become too large. As a result, the ratios of nitrogen to phosphorus, silicon, and iron and other nutrients are altered. This alteration may induce changes in phytoplankton, produce noxious or toxic brown or red algal blooms (which are called "red tides"), or stimulate other plant growth. The algal blooms and plant growth produce a shadow and cause the death of other plants in the water, which depletes the oxygen content of the water (hypoxia) when the plants die, sink, and decay. Such eutrophication can make the bottom strata of water unihabitable for both marine animals (such as fish and shellfish) and aquatic plants. It can progress to virtually the complete depth of the water. It is estimated that between 12% and 44% of the nitrogen loading of coastal water bodies comes from the air.[40] Inland lakes are also affected in this way.

Another dimension of the problem is that high temperature combustion can convert sulfur in fuel to SO_2 and SO_3. While SO_2 is toxic and forms sulfurous acid when dissolved in water, SO_3 is both toxic and hygroscopic (moisture absorbing) and forms sulfuric acid by combining with moisture in the atmosphere. SO_2 and SO_3 form sulfites and sulfates when their acids are neutralized. Both of these acids can form solid particles by reacting with ammonia in air. SO_2 and SO_3 also contribute to pH (acidity) changes in water, which can adversely affect both land and aquatic life. Therefore, both NOx and SOx from combustion can kill plants and animals.

CAPITA has shown that there are about equal amounts by weight of sulfate/sulfite, nitrate and organic particles making up 90% of Particulate Matter less than 2.5 microns in aerodynamic diameter (PM-2.5). This was confirmed by Brigham Young University researchers. The Six Cities Study, published in the *New England Journal of Medicine* in 1990, has shown that illness and premature death are closely correlated with the amount of PM-2.5 in the air. Therefore, there is epidemiological data indicting nitrogen oxides, sulfur oxides, and/or organic compounds as PM-2.5 aerosols. There is currently no evidence that separately examines the health effects of each of these substances. PM-2.5 usually appear as smog, smoke, white overcast, haze, or fog which does not clear when air warms up. Brown smog is colored by nitrogen dioxide.

Because the nitric acid, sulfurous acid and sulfuric acid react with ammonia in air to form solid crystals that are much smaller than 2.5 microns and can be nucleation sites for particle growth, we need to be concerned about each of these pollutants. Some research indicates that even insoluble particles much smaller than 2.5 microns in size can exhibit severe toxic effects.[38] The smallest particles that have shown toxicity have a diameter of about 3% to 5% of the wavelength of any color of visible light. Therefore, these particles are too small to even scatter light and cannot even be detected optically.

Acid deposition occurs from airborne acidic or acidifying compounds, principally sulfates (SO_4^{-2}) and nitrates (NO_3^{-1}), that can be transported over long distances before returning to earth. This occurs through rain or snow (wet deposition), fog or cloud water (cloud deposition), or transfer of gases or particles (dry deposition). While severity of damage depends on the sensitivity of the receptor, acid deposition and NOx "represent a threat to natural resources, ecosystems, visibility, materials, and public health."(section 401(a)(1) of the Clean Air Act).[40]

WHAT ABATEMENT AND CONTROL PRINCIPLES APPLY?

NOx abatement and control technology is a relatively complex issue. We shall try to provide a structure to the spectrum of NOx pollution prevention and control technologies by first giving the principles that are used. Then we shall describe the more successful pollution prevention and emission control technologies and strategies.

Please note that abatement and control of NOx from nitric acid manufacturing and "pickling" baths differs from abatement and control at combustion sources. Combustion sources all have NOx in a large flow of flue gas, while nitric acid manufacturing plants and pickling baths try to contain the NOx. Wet scrubbers (absorbers) can control NOx emissions from acid plants and pickling, and can use either alkali in water, water alone, or hydrogen peroxide as the liquid that captures the NOx.[3] The wet scrubber operates by liquid flowing downward by gravity through a packing medium, opposed by an upward flow of gas. Scrubbers operate on the interchange of substances between gas and liquid. This requires that the height of the absorber, type of packing, liquid flow, liquid properties, gas properties, and gas flow should collectively cause a scrubber to have the desired control efficiency. Chapter 9 of the OAQPS Control Cost Manual provides guidance on the application, sizing, and cost of these scrubbers (referred to as gas absorbers). Also, Table 16 in this Bulletin presents some information for non-combustion NOx sources. Other then that, non-combustion NOx sources are not addressed in this Bulletin.

For combustion sources, this Bulletin defines abatement and emission control principles and states the Destruction or Removal Efficiency (DRE) that each successful technology is capable of achieving. The effectiveness of pollution prevention measures in reducing NO and NO_2 generation also is expressed in terms of relative DRE; i.e., the amount NOx generation is reduced by using a prevention technology compared to NOx generation when not using that technology. Then, specific boiler types and combustion systems and applicable NOx technologies for each system are discussed. Finally, the cost of these technologies is considered.

Many new combustion systems incorporate NOx prevention methods into their design and generate far less NOx then similar but older systems. As a result, considering DRE (even a relative DRE) for NOx may be inappropriate. Comparing estimated or actual NOx emissions from a new, well-designed system to NOx emitted by a similar well-controlled and operated older system may be the best way of evaluating how effectively a new combustion system minimizes NOx emissions.

Table 2 lists principles or methods that are used to reduce NOx. Basically there are six

principles, with the seventh being an intentional combination of some subset of the six.

Table 2. NOx Control Methods [6,7]

Abatement or Emission Control Principle or Method	Successful Technologies	Pollution Prevention Method (P2) or Add-on Technology (A)
1. Reducing peak temperature	Flue Gas Recirculation (FGR) Natural Gas Reburning Low NOx Burners (LNB) Combustion Optimization Burners Out Of Service (BOOS) Less Excess Air (LEA) Inject Water or Steam Over Fire Air (OFA) Air Staging Reduced Air Preheat Catalytic Combustion	P2 P2 P2 P2 P2 P2 P2 P2 P2 P2 P2
2.Reducing residence time at peak temperature	Inject Air Inject Fuel Inject Steam	P2 P2 P2
3. Chemical reduction of NOx	Fuel Reburning (FR) Low NOx Burners (LNB) Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction (SNCR)	P2 P2 A A
4. Oxidation of NOx with subsequent absorption	Non-Thermal Plasma Reactor Inject Oxidant	A A
5. Removal of nitrogen	Oxygen Instead Of Air Ultra-Low Nitrogen Fuel	P2 P2
6. Using a sorbent	Sorbent In Combustion Chambers Sorbent In Ducts	A A
7. Combinations of these Methods	All Commercial Products	P2 and A

Method 1. Reducing Temperature -- Reducing combustion temperature means avoiding the stoichiometric ratio (the exact ratio of chemicals that enter into reaction). Essentially, this technique dilutes calories with an excess of fuel, air, flue gas, or steam. Combustion controls use different forms of this technique and are different for fuels with high and low nitrogen content.

Control of NOx from combustion of high nitrogen content fuels (e.g., coal) can be understood by the net stoichiometric ratio. Control of the NOx from combustion of low nitrogen fuels (such as gas and oil) can be seen as lean versus rich fuel/air ratios. Either way, this technique avoids the ideal stoichiometric ratio because this is the ratio that produces higher temperatures that generate higher concentrations of thermal NOx.

Combustion temperature may be reduced by: (1) using fuel rich mixtures to limit the amount of oxygen available; (2) using fuel lean mixtures to limit temperature by diluting energy input; (3) injecting cooled oxygen-depleted flue gas into the combustion air to dilute energy; (4) injecting cooled flue gas with added fuel; or (5) injecting water or steam. Low-NOx burners are based partially on this principle.[8,9,10] The basic technique is to reduce the temperature of combustion products with an excess of fuel, air, flue gas, or steam. This method keeps the vast majority of nitrogen from becoming ionized (i.e., getting a non-zero valence).

Method 2. Reducing Residence Time -- Reducing residence time at high combustion temperatures can be done by ignition or injection timing with internal combustion engines. It can also be done in boilers by restricting the flame to a short region in which the combustion air becomes flue gas. This is immediately followed by injection of fuel, steam, more combustion air, or recirculating flue gas. This short residence time at peak temperature keeps the vast majority of nitrogen from becoming ionized. This bears no relationship to total residence time of a flue gas in a boiler.

Method 3. Chemical Reduction of NOx – This technique provides a chemically reducing (i.e., reversal of oxidization) substance to remove oxygen from nitrogen oxides. Examples include Selective Catalytic Reduction (SCR) which uses ammonia, Selective Non-Catalytic Reduction (SNCR) which use ammonia or urea, and Fuel Reburning (FR). Non-thermal plasma, an emerging technology, when used with a reducing agent, chemically reduces NOx. All of these technologies attempt to chemically reduce the valence level of nitrogen to zero after the valence has become higher.[11] Some low-NOx burners also are based partially on this principle.

Method 4. Oxidation of NOx -- This technique intentionally raises the valence of the nitrogen ion to allow water to absorb it (i.e., it is based on the greater solubility of NOx at higher valence). This is accomplished either by using a catalyst, injecting hydrogen peroxide, creating ozone within the air flow, or injecting ozone into the air flow. Non-thermal plasma, when used without a reducing agent, can be used to oxidize NOx. A scrubber must be added to the process to absorb N_2O_5 emissions to the atmosphere. Any resultant nitric acid can be either neutralized by the scrubber liquid and then sold (usually as a calcium or ammonia salt), or collected as nitric acid to sell to customers.[12, 49]

Method 5. Removal of nitrogen from combustion -- This is accomplished by removing nitrogen as a reactant either by: (1) using oxygen instead of air in the combustion process; or (2) using ultra-low nitrogen content fuel to form less fuel NOx. Eliminating nitrogen by using oxygen tends to produce a rather intense flame that must be subsequently and suitably diluted. Although Method 2 can lower the temperature quickly to avoid forming excessive NOx, it cannot

eliminate nitrogen oxides totally if air is the quench medium. Hot flue gas heats the air that is used to quench it and this heating generates some thermal NOx. This method also includes reducing the net excess air used in the combustion process because air is 80% nitrogen. Using ultra-low-nitrogen content fuels with oxygen can nearly eliminate fuel and prompt NOx.[13]

Method 6. Sorption, both adsorption and absorption -- Treatment of flue gas by injection of sorbents (such as ammonia, powdered limestone, aluminum oxide, or carbon) can remove NOx and other pollutants (principally sulfur). There have been successful efforts to make sorption products a marketable commodity. This kind of treatment has been applied in the combustion chamber, flue, and baghouse. The use of carbon as an adsorbent has not led to a marketable product, but it is sometimes used to limit NOx emissions in spite of this. The sorption method is often referred to as using a dry sorbent, but slurries also have been used. This method uses either adsorption or absorption followed by filtration and/or electrostatic precipitation to remove the sorbent.

Method 7. Combinations of these methods -- Many of these methods can be combined to achieve a lower NOx concentration than can be achieved alone by any one method. For example, a fuel-rich cyclone burner (Method 1) can be followed by fuel reburn (Method 3) and over-fire air (Method 1). This has produced as much as a 70% reduction in NOx.[55] Other control technologies that are intended to primarily reduce concentrations of sulfur also strongly affect the nitrogen oxide concentration. For example, the SOx-NOx-ROx-Box (SNRB) technology uses a limestone sorbent in the flue gas from the boiler to absorb sulfur. This is followed by ammonia injection and SCR using catalyst fibers in the baghouse filter bags. The sulfur is recovered from the sorbent and the sorbent regenerated by a Claus process. This has demonstrated removal of up to 90% of the NOx along with 80% of the SOx.[39, 42] EBARA of Japan reported that an electron beam reactor with added ammonia removed 80% of the SO_2 and 60% of the NOx for a utility boiler in China.[54] FLS Milo and Sons reported at the same symposium that 95% of the SO_2 and 70%-90% of the NOx were removed in several demonstrations of their SNAP technology, which is based upon an aluminum oxide adsorber with Claus regeneration.[56]

WHAT ABATEMENT TECHNOLOGIES ARE AVAILABLE?

In this report existing NOx abatement technologies are divided into two categories, external combustion applications (e.g., boilers, furnaces and process heaters) and internal combustion applications (e.g., stationary internal combustion engines and turbines). These categories are further subdivided into pollution prevention (which reduces NOx generation) and add-on control technologies (which reduces NOx emissions).

EXTERNAL COMBUSTION

For external combustion applicable technologies are shown in Table 3 (based on Table 2 in Select the Right NOx Control Technology, Stephen Wood, Chemical Engineering Progress, January 1994).

Table 3. External Combustion NOx Limiting Technologies					
Technique	**Description**	**Advantages**	**Disadvantages**	**Impacts**	**Applicability**
Less Excess Air (LEA)	Reduces oxygen availability	Easy modification	Low NOx reduction	High CO Flame length Flame stability	All fuels
Off Stoichiometric a. Burners Out of Service (BOOS) b. Over Fire Air (OFA)	staged combustion	Low cost No capital cost for BOOS	a. Higher air flow for CO b. high capital cost	Flame length Fan capacity Header pressure	All fuels Multiple burners for BOOS
Low NOx Burner (LNB)	Internal staged combustion	Low operating cost Compatible FGR	Moderately high capital cost	Flame length Fan capacity Turndown stability	All fuels
Flue Gas Recirculation (FGR)	<30% flue gas recirculated with air, decreasing temperature	High NOx reduction potential for low nitrogen fuels	Moderately high capital cost and operating cost Affects heat transfer and system pressures	Fan capacity Furnace pressure Burner pressure drop Turndown stability	All fuels Low nitrogen fuels
Water/Steam Injection	Reduces flame temperature	Moderate capital cost NOx reduction similar to FGR	Efficiency penalty Fan power higher	Flame stability Efficiency penalty	All fuels as Low nitrogen fuels
Reduced Air Preheat	Air not preheated, reduces flame temperature	High NOx reduction potential	Significant efficiency loss (1% per 40 F)	Fan capacity Efficiency penalty	All fuels Low nitrogen fuels
Selective Catalytic reduction (SCR) (add-on technology)	Catalyst located in the air flow, promotes reaction between ammonia and NOx	High NOx removal	Very high capital cost High operating cost Catalyst siting Increased pressure drop Possible water wash required	Space requirements Ammonia slip Hazardous waste Disposal	All fuels

Table 3. External Combustion NOx Limiting Technologies					
Technique	**Description**	**Advantages**	**Disadvantages**	**Impacts**	**Applicability**
Selective Non-Catalytic Reduction (SNCR) (add-on technology) a. urea b. ammonia	Inject reagent to react with NOx	a. Low capital cost Moderate NOx removal Non-toxic chemical b. Low operating cost Moderate NOx removal	a. Temperature dependent NOx reduction less at lower loads b. Moderately high capital cost Ammonia storage, handling, injection system	a. Furnace geometry Temperature profile b. Furnace geometry Temperature profile	All fuels
Fuel Reburning	Inject fuel to react with NOx	Moderate cost Moderate NOx removal	Extends residence time	Furnace temperature profile	All fuels (pulverized solid)
Combustion Optimization	Change efficiency of primary combustion	Minimal cost	Extends residence time	Furnace temperature profile	Gas Liquid fuels
Catalytic Combustion	Catalyst causes combustion to be at low temperature	Lowest possible NOx	Very high capital cost High operating cost Catalyst siting	Space requirements Disposal	Gas Liquid fuels
Non-Thermal Plasma	Reducing agent ionized or oxidant created in flow	Moderate cost Easy siting High NOx removal	Fouling possible Ozone emission possible	Uses electrical power	All fuels
Inject Oxidant	Chemical oxidant injected in flow	Moderate cost	Nitric acid removal	Add-on	All fuels
Oxygen instead of Air	Uses oxygen to oxidize fuel	Moderate to high cost Intense combustion	Eliminates prompt NOx Furnace alteration	Equipment to handle oxygen	All fuels
Ultra-Low Nitrogen Fuel	Uses low -nitrogen fuel	Eliminates fuel NOx No capital cost	Slight rise in operating cost	Minimal change	All ultra-low nitrogen fuels

Table 3. External Combustion NOx Limiting Technologies					
Technique	**Description**	**Advantages**	**Disadvantages**	**Impacts**	**Applicability**
Use Sorbents (add-on technology) in: a. Combustion b. Duct to Baghouse c. Duct to Electrostatic Precipitator	Use a chemical to absorb NOx or an adsorber to hold it	Can control other pollutants as well as NOx Moderate operating cost	Cost of handling sorbent Space for the sorbent storage and handling	Add-on	All fuels
Air Staging	Admit air in separated stages	Reduce peak combustion temperature	Extend combustion to a longer residence time at lower temperature	Adds ducts and dampers to control air Furnace modification	All fuels
Fuel Staging	Admit fuel in separated stages	Reduce peak combustion temperature	Extend combustion to a longer residence time at lower temperature	Adds fuel injectors to other locations Furnace modification	All fuels

EXTERNAL COMBUSTION: POLLUTION PREVENTION METHODS

LESS EXCESS AIR (LEA)

Excess air flow for combustion has been correlated to the amount of NOx generated. Limiting the net excess air flow to under 2% can strongly limit NOx content of flue gas. Although there are fuel-rich and fuel-lean zones in the combustion region, the overall net excess air is limited when using this approach.[43]

BURNERS OUT OF SERVICE (BOOS)

Multiple-burner equipment can have part of an array of burners with some "burners out of service" (not feeding fuel, but supplying air or flue gas). This allows the burners around them to supply fuel and air to air or flue gas flowing from the BOOS. The result is combustion by stages with temperature always lower than when all burners are in service. Thus, thermal NOx is lower. The degree to which NOx generation is reduced depends upon the spatial relationship of the BOOS to the other burners.[44]

OVER FIRE AIR (OFA)

When primary combustion uses a fuel-rich mixture, use of OFA completes the combustion. Because the mixture is always off-stoichiometric when combustion is occurring, the temperature is held down. After all other stages of combustion, the remainder of the fuel is oxidized in the over fire air. This is usually not a grossly excessive amount of air.

LOW NOx BURNERS (LNB)

A LNB provides a stable flame that has several different zones. For example, the first zone can be primary combustion. The second zone can be Fuel Reburning (FR) with fuel added to chemically reduce NOx. The third zone can be the final combustion in low excess air to limit the temperature. There are many variations on the LNB theme of reducing NOx. The LNB has produced up to 80% DRE.[17,18,32,33] This can be one of the least expensive pollution prevention technologies with high DRE. LNB have had problems with designs that had flame attaching to the burners, resulting in a need for maintenance. We believe that these design problems should now be a thing of the past.

FLUE GAS RECIRCULATION (FGR)

Recirculation of cooled flue gas reduces temperature by diluting the oxygen content of combustion air and by causing heat to be diluted in a greater mass of flue gas. Heat in the flue gas can be recovered by a heat exchanger. This reduction of temperature lowers the NOx concentration that is generated. If combustion temperature is held down to below 1,400°F, the thermal NOx formation will be negligible.[50]

WATER OR STEAM INJECTION

Injection of water or steam causes the stoichiometry of the mixture to be changed and adds steam to dilute calories generated by combustion. Both of these actions cause combustion temperature to be lower. If temperature is sufficiently reduced, thermal NOx will not be formed in as great a concentration.

REDUCED AIR PREHEAT

Air is usually preheated to cool the flue gases, reduce the heat losses, and gain efficiency. However, this can raise the temperature of combustion air to a level where NOx forms more readily. By reducing air preheat, the combustion temperature is lowered and NOx formation is suppressed. This can lower efficiency, but can limit NOx generation.

FUEL REBURNING (FR)

Recirculation of cooled flue gas with added fuel (this can be natural gas, pulverized coal, or even oil spray) causes dilution of calories, similar to FGR, and primary combustion temperature can be lowered. Also, when added as a secondary combustion stage, the presence of added fuel chemically reduces newly generated NOx to molecular nitrogen. Added fuel is only partially consumed in reducing NOx and burning is completed in a later stage using either combustion air nozzles or over-fire-air. This technique has been demonstrated to be effective with residence times from 0.2 seconds to 1.2 seconds and has achieved up to 76% DRE. [17]

COMBUSTION OPTIMIZATION

Combustion optimization refers to the active control of combustion. In a natural gas fired boiler, by decreasing combustion efficiency from 100% to 99%, NOx generation dropped to a much more acceptable level.[14,15] For coal-fired boilers a 20% to 60% reduction in NOx has been experienced. These active combustion control measures seek to find an optimum combustion efficiency and to control combustion (and hence emissions) at that efficiency. Another approach uses a neural network computer program to find the optimum control point.[16] Still another approach is to use software to optimize inputs for the defined output.[52,53]

One vendor decreases the amount of air that is pre-mixed with fuel from the stoichiometric ratio (ratio that produces the hottest flame) to lengthen the flame at the burner and reduce the rate of heat release per unit volume. This can work where the boiler tubes are far enough away from the burner. Carbon monoxide, unburned fuel, and partially burned fuel that result can then be subsequently oxidized in over-fire-air at a lower temperature. Combustion must be optimized for the conditions that are encountered. 50% DRE has been reported.[14]

AIR STAGING

Combustion air is divided into two streams. The first stream is mixed with fuel in a ratio that

produces a reducing flame. The second stream is injected downstream of the flame and makes the net ratio slightly excess air compared to the stoichiometric ratio. DRE up to 99% have been reported.[51]

FUEL STAGING

This is staging of combustion using fuel instead of the air. Fuel is divided into two streams. The first stream feeds primary combustion that operates in a reducing fuel to air ratio. The second stream is injected downstream of primary combustion, causing the net fuel to air ratio to be only slightly oxidizing. Excess fuel in primary combustion dilutes heat to reduce temperature. The second stream oxidizes the fuel while reducing the NOx to N_2. This is reported to achieve a 50% DRE.[51]

OXYGEN INSTEAD OF AIR FOR COMBUSTION

An example of this is a cyclone burner where the flame is short and intense. Excess fuel air or steam, injected just after the combustion chamber per Method 2 is sufficient to rapidly quench the flue gas to below NOx formation temperature. Combustion can then be completed in over-fire air. Oxygen can now be separated from air at a low enough cost to make this economical.[13] This technique has reduced NOx by up to 20%[23] in burners using conventional fuel. This technique also is usable with low-NOx burners to prevent the prompt NOx from being formed.

INJECTION OF OXIDANT

The oxidation of nitrogen to its higher valence states makes NOx soluble in water. When this is done a gas absorber can be effective. Oxidants that have been injected into the air flow are ozone, ionized oxygen, or hydrogen peroxide. Non-thermal plasma generates oxygen ions within the air flow to achieve this. Other oxidants have to be injected and mixed in the flow. Nitric acid can be absorbed by water, hydrogen peroxide, or an alkaline fluid. Calcium or ammonia dissolved in the water can make an alkaline fluid that will react with nitric and sulfuric acids to produce a nitrate or sulfate salt that can be recovered. Alternatively, using water or hydrogen peroxide to absorb NOx can provide nitric acid for the commercial market.

CATALYTIC COMBUSTION

Use of a catalyst to cause combustion to occur below NO formation temperatures can provide a suitable means of limiting temperature. This technique is not used often because it is very load sensitive. However, where it is used, catalytic combustion can achieve less than a 1 ppm concentration of NOx in the flue gas.

ULTRA-LOW NITROGEN FUELS

These fuels can avoid NOx that results from nitrogen contained in conventional fuels. The result can be up to a 70% reduction in NOx emissions.[43] Now there are ultra-low-nitrogen liquid fuel

oils. These oils contain 15-20 times less nitrogen than standard No. 2 fuel oil. This oil is now commercially available and competitively priced. Ultra-low-nitrogen oil is most frequently used in Southern California where the air pollution is particularly a problem. Natural gas can be considered a low-nitrogen fuel. Coke (the quenched char from coal) can also be an ultra-low-nitrogen fuel because nitrogen in the volatile fraction of the coal is removed in making coke.

NON-THERMAL PLASMA

Using methane and hexane as reducing agents, non-thermal plasma has been shown to remove NOx in a laboratory setting with a reactor duct only 2 feet long. The reducing agents were ionized by a transient high voltage that created a non-thermal plasma. The ionized reducing agents reacted with NOx and achieved a 94% DRE. There are indications that an even higher DRE can be achieved. A successful commercial vendor uses ammonia as a reducing agent to react with NOx in an electron beam generated plasma. Such a short reactor can meet available space requirements for virtually any plant. The non-thermal plasma reactor could also be used without reducing agent to generate ozone and use that ozone to raise the valence of nitrogen for subsequent absorption as nitric acid.

EXTERNAL COMBUSTION: ADD-ON CONTROL TECHNOLOGY

Add-on controls are applicable to a broad range of sources and fuels. This differs from the pollution prevention techniques listed above in that the prevention techniques must be adapted to the circumstances of their use.

SELECTIVE CATALYTIC REDUCTION (SCR)

SCR uses a catalyst to react injected ammonia to chemically reduce NOx. It can achieve up to a 94% DRE[34] and is one of the most effective NOx abatement techniques. However, this technology has a high initial cost. In addition, catalysts have a finite life in flue gas and some ammonia "slips through" without being reacted. SCR has historically used precious metal catalysts, but can now also use base-metal and zeolite catalysts. The base-metal and zeolite catalysts operate at much different temperatures then the precious metal catalysts.[11]

SELECTIVE NON-CATALYTIC REDUCTION (SNCR)

In SNCR ammonia or urea is injected within a boiler or in ducts in a region where temperature is between 900°C and 1100°C. This technology is based on temperature ionizing the ammonia or urea instead of using a catalyst or non-thermal plasma. This temperature "window" – which is reported differently by various authors -- is important because outside of it either more ammonia "slips" through or more NOx is generated than is being chemically reduced. The temperature "window" is different for urea and ammonia. Reduction of the NOx by SNCR can have up to a 70% DRE.[23,35,43]

SORPTION – BOTH ADSORPTION AND ABSORPTION

Several methods are used to inject and remove adsorbent or absorbent. One method sprays dry powdered limestone into the flue gas. The limestone then reacts with both sulfuric acid and nitric acid. There also is a spray dryer approach that sprays a slurry of powdered limestone and aqueous ammonia into the flue gas. The limestone preferentially reacts with the sulfur while the ammonia preferentially reacts with the NOx. In-duct injection of dry sorbents is another example of this technique and can reduce pollutants in three stages: (1) in the combustion chamber, (2) in the flue gas duct leading to the baghouse, and (3) in the flue gas duct leading to the electrostatic precipitator. The by products formed by sorption are gypsum (calcium sulfate) that is sold to make wallboard, and ammonium nitrate that can be sold to make either an explosive or a fertilizer. Sorption is reported to have up to a 60% DRE.[23, 31] Another version uses carbon injected into the air flow to finish the capture of NOx. The carbon is captured in either the baghouse or the ESP just like other sorbents. There are many absorbents and adsorbents available.

COMBINED TECHNOLOGY APPROACHES

Very seldom is only one method or principle used alone. The choice depends upon the type of combustion system, type of boiler or other energy conversion device, and type of fuel used. Available technologies will be narrowed by consideration of turndown ratio, stability of combustion, availability or access to burners, air supply controls, fuel impurities, and cost among other factors.

There are many examples and here are a few of them. Selective catalytic reduction of NOx to N_2 can be followed by selective oxidation of sulfur dioxide to sulfur trioxide. Then sulfuric acid is formed followed by scrubbing sulfuric acid from the flue gas.[30]

LNB can be used in conjunction with SCR or SNCR to achieve a greater overall DRE than any of these can achieve alone. Water/steam injection can be used with SCR to achieve a DRE greater than SCR can achieve alone. Fuel reburning and SCR can be used together as well as separately, to get the maximum NOx reduction.[57]

INTERNAL COMBUSTION

Now we turn to internal combustion, which usually occurs at elevated pressures. Again, we divide the technologies between pollution prevention techniques and add-on technologies. This is shown in Table 4.

These techniques can be used in combination. Pollution prevention techniques do not have to be used separately. Add-on techniques could be used sequentially after a pollution prevention technique when they do not impose conflicting demands on the process.

Table 4. Internal Combustion NOx Limiting Technologies

Pollution Prevention	Add-On Control
Low-NOx Burners (LNB)	Selective Catalytic Reduction (SCR)
Steam/Water Injection	Selective Non-Catalytic Reduction (SNCR)
Catalytic Combustion	Non-Selective Catalytic Reduction (NSCR)
Air-Fuel Ratio and Ignition Type	Non-Thermal Plasma
Pre-Stratified Charge	
Lean Burn	

INTERNAL COMBUSTION: POLLUTION PREVENTION METHODS

LOW NOx BURNERS (LNB)

Combining the use of LNB with closely controlled air/fuel ratio and water/steam injection can yield emissions as low as 10 ppm from gas turbines.[46]

STEAM/ WATER INJECTION

To reduce combustion temperature, steam or water can be mixed with the air flow. This lowers combustion temperature to below 1,400°F to limit NOx generation to about 40 ppm.[46] This can cause the concentration of CO and unburned hydrocarbons emitted from a turbine to be increased. However, these can be burned by either a catalyst bed, afterburner, or another stage of combustion. This otherwise wasted fuel and heat can also be recovered in co-generation boilers.

CATALYTIC COMBUSTION

A catalyst is used to react fuel with air at a lower temperature than normal combustion at which generation of significant amounts of NOx does not occur. Emissions under 1 ppm NOx have been reported.[46] However, if this combustion is for a turbine, turbine efficiency may depend upon achieving a higher temperature. When a catalyst is present, you also need to assure that NOx will not be formed at the combustion temperature that results.

This technology has a relatively high capital and operation and maintenance cost because there is both a substantial initial investment and a replacement cost for the catalyst. The need for replacement and, therefore, replacement cost are usually driven by impurities in the fuel. However, catalytic combustion generates possibly the lowest level of thermal NOx.

AIR-FUEL RATIO AND IGNITION TYPE

For internal combustion reciprocating engines, retardation of injection or spark ignition, or an air-fuel ratio that departs from stoichiometric conditions will reduce peak temperature. Lower peak temperature will limit the amount of NOx formation. This technique can achieve up to 50% control efficiency.[19, 48]

When a three-way catalyst is used for spark ignition engines, exhaust gas must have no more than 0.5% oxygen. This technique can be up to 98% effective.

The use of plasma ignition (an alternating current or AC system) instead of a direct current (DC) spark ignition system can also allow a greater fuel-lean departure from the stoichiometric ratio. NOx emissions from internal combustion engines using plasma ignition have been reported to be reduced by up to 97%.[20,21, 45]

Delaying injection of fuel in a compression ignition (diesel) engine can reduce the NOx emissions. The amount of this reduction will depend upon the engine, valving, and fuel. Excessive timing retard can cause combustion instability or misfire.[48] However, some claims of high effectiveness are to be found with ostensibly excessive retard.

PRE-STRATIFIED CHARGE (PSC)

PSC refers to an engine equipped with a pre-combustion chamber that receives a rich enough air/fuel mixture to ignite dependably. This pre-combustion chamber fires a jet of flame into the main combustion chamber (cylinder). The main combustion chamber has a fuel-lean mixture that needs pre-combustion flame to ignite it reliably. The injected flame also produces a swirl in the main combustion chamber that acts like stratified charge combustion. This dependably ignites the lean main cylinder mixture. The PSC can achieve NOx emissions of 2 grams/horsepower-hour (g/hp-hr) or 140 ppm.[48]

LEAN BURN

Natural gas fueled engines that operate with a fuel-lean air/fuel ratio are capable of low NOx emissions. These can achieve less than 1.0 gram/brake horsepower-hour according to the RACT-BACT-LAER Clearinghouse (RBLC) (http://www.epa.gov/ttn/catc, then select RBLC).

INTERNAL COMBUSTION ADD-ON CONTROL TECHNOLOGY

SELECTIVE CATALYTIC REDUCTION (SCR)

As with boilers, SCR can be used to obtain up to a 90% DRE of NOx. When used with a LNB or steam/water injection, NOx can be reduced to 5-10 ppm.[46] With compression ignition engines, zeolite catalysts achieve a DRE of 90+%, while base-metal catalysts can achieve a 80% to 90% DRE.[48]

NON-SELECTIVE CATALYTIC REDUCTION (NSCR)

NSCR is the same technique used in automobile applications as a three-way catalytic converter. It does not require injection of a reducing agent because it uses unburned hydrocarbons as a reducing agent. The catalyst requires that exhaust have no more than 0.5% oxygen. This technique uses a fuel rich mixture that, combined with back pressure from exhaust flow through the catalyst, increases the brake specific fuel consumption of the engine. However, NOx control of 90% to 98% can be achieved.[48]

NON-THERMAL PLASMA REACTORS

This approach uses a non-thermal plasma to ionize ammonia, urea, hexane, methane or other reducing agents injected into a flue gas. Combined with the effect of temperature, non-thermal plasma ionizes the reducing agent that reacts with nitrogen oxides achieving a 94% DRE. This decreases the amount of reducing chemicals that "slips" through unreacted.[20,44] The use of non-thermal plasma was developed to ionize pollutants and act as a catalyst to control NOx in diesel exhaust.[36]

DO FUELS AND COMBUSTION TYPE AFFECT ABATEMENT?

Yes they do. Here again, we find a spectrum of types, almost enough to make every gas turbine, internal combustion engine, boiler, or furnace seem unique. The type of fuel can vary with the vein of the mine from which coal was obtained, the well in the oilfield from which crude oil came, the refinery for petroleum based fuels, or the supplier of natural gas. Thus the concentration of impurities will vary between sources, refineries, and suppliers. Even "natural gas" (methane) may contain some "supplier gas" (propane, butane, and carbon monoxide) which will cause the composition of "natural gas" to vary.

The type of combustion system (low-NOx burner, over-fire air, tangential firing, wall firing, etc) also will sometimes limit options. Each type of boiler, each type of fuel, each combustion system, and each construction of a boiler puts constraints on what is possible. It is not possible to treat each combination of combustion system and fuel in detail in this Technical Bulletin; however, we will try to show the picture while painting with broad strokes.

The choice of fuel and combustion system often depends upon: (1) what can or cannot be adjusted; (2) whether ducts are suitable for sorption; (3) what the effect on boiler maintenance will be; (4) the temperature profile in the flow: (5) how the combustion system can be modified; (6) what types of burners can be used; and (7) what can either be added or modified. The list does not end there, but continues. Let us consider some fuels with these limitations in mind.

SOLID FUELS

In burning a solid fuel (such as coal), combustion control is achieved by first getting the primary burner to gasify the volatile fraction of a fuel. The volatile fraction is carried away from char by

air flow, oxidized in the air flow, and becomes flue gas. Char needs more combustion air to burn and provide further heat, part of which is used to volatilize additional fuel. To control combustion temperature, you traditionally would limit combustion air through the char fraction. The volatile fraction is oxidized in over-fire-air or a secondary stage of burner and must have its air separately controlled. The balance of combustion air between these stages must be adjusted for composition of fuel being used, boiler loading, and transient loads. Because all of these parameters will vary continually, provisions to make balancing adjustments dynamically are recommended.

Pulverized coal can be burned similar to oil. The flame is usually well defined and, depending on particle size, char may remain in suspension in flue gas throughout burning. The volatile fraction burns in air even as char is burned. If the particles are too coarse, char will continue burning on its trajectory after leaving the flame, but will stop burning at some point. The trade jargon for this is " unburned carbon (UBC)," "carbon in the ash (CIA)," or "loss of ignition (LOI)." These terms refer to carbon in char that does not burn along the trajectory. UBC is minimized by grinding particles finer and classifying particles so that larger ones are returned to the roller mill or grinder. Particles will become fly ash if they are small enough. UBC ranging from 0.5% to 5% is considered acceptable. Therefore, particle size at ignition is important. The major concerns are to control stoichiometry and combustion temperature to minimize unburned carbon in ash.

Biomass is another solid fuel, but burning biomass char is less of a concern than with coal. Biomass cannot be pulverized to small particles, but can burn to ash in a short time. As with the burning of all char, ash and fly ash are problems, but can be treated with a slag tap or ash pit, baghouse, and/or electrostatic precipitator.

LIQUID FUELS

Liquid fuels burn like the volatile fraction of solid fuel provided that the droplets are small enough. Liquid fuels usually have less nitrogen content than solid fuels. Combustion of liquids and gases can be controlled much more readily than char from solid fuel because combustion is less dependent on the history of the past few minutes of demand. Combustion is also completed essentially without residual ash. The fuel-air ratio can be used to control combustion temperature and can be adjusted to minimize NOx generation. The flame can be well-defined and combustion is essentially completed within the flame. Therefore, burning oil or liquid-from-coal or liquid-from-gas is different from burning coal because there is usually less nitrogen in the fuel, a lack of char, complete burning within the flame and a lack of ash.

SEMI-SOLID FUELS

Semi-solid fuels are residuals from refineries. They are not clean burning like distillates and often are not even liquid at room temperature. Many impurities typically found in crude oil are concentrated in semi-solid residual fuel. These fuels can contain more nitrogen than coal, but usually contain less sulfur.[50] Therefore, semi-solid fuels are intermediate between coal and oil. They often have somewhat less impurities than coal (although they can have more impurities),

but they do produce ash.

GAS FUEL

Natural gas is desulfurized before it is sent in a pipeline. Therefore, natural gas has almost no sulfur, essentially no impurities, and no ash. The only thing that varies is heat content per cubic meter. This variance is caused by natural gas producers supplementing natural gas with propane, liquified petroleum gas (butane), carbon monoxide, or other gaseous fuel. As a result, air to fuel ratio must be controllable to allow for changes in the stoichiometric ratio.

COMBUSTION SYSTEMS

To take advantage of a specific NOx abatement technology, a combustion system must either have certain features in place, or needed system modifications must be technically and economically feasible. Therefore, when identifying applicable pollution prevention and emission control technologies, we must first consider combustion system design. The major types of combustion systems are shown in Table 5.[23]

Table 5. Common Combustion Systems

Type of Combustion Unit	Fuel
Dry bottom boilers - wall-fired, front-fired or opposed-fired	pulverized coal, gas, or liquid
Dry bottom boilers - tangentially fired	pulverized coal, gas, or liquid
Wet bottom (slag tap) boilers - cyclone-type burners	pulverized coal, gas, or liquid
Fluidized bed	coal
Stokers with traveling grate.	crushed coal
Stokers with spreader grate	crushed coal.
Gas turbines	gas and liquid
Internal combustion engines	gas and liquid

Each NOx abatement technology has different implementations, development histories, and, therefore, commercial status. Selection of a technology must occur after an engineering study to determine technical and economic feasibility of each NOx technology. This includes how each technology can be implemented and its cost. Options may be limited by inability to adjust combustion system air flow appropriately, ducts that are at the wrong temperature, or ducts that

are too short to provide adequate mixing. These problems can be solved, but may require too much modification to make them economical.

DRY BOTTOM BOILERS - WALL-FIRED, FRONT-FIRED or OPPOSED-FIRED

Dry bottom pulverized coal, gas, and liquid fuel wall-fired boilers have used low-NOx burners to inject fuel and air from lower walls. Front-fired boilers have burners on one wall. Opposed-fired boilers have burners on front and back walls. These boilers typically use methods that reduce peak temperature, reduce residence time at peak temperature, or chemically reduce NOx (Methods 1, 2 & 3). These methods are used for large utility boilers in which combustion efficiency is all-important. NOx oxidation with absorption and removal of nitrogen (Methods 4 and 5) represent newer technologies that may be applied in the future. Using a sorbent (Method 6) is already in use for some boilers. See Table 6 for NOx technologies used for dry bottom wall-fired, front-fired or opposed-fired boilers.

Table 6: NOx technologies currently used for dry bottom wall-fired, front-fired or opposed-fired boilers.

NOx Abatement Method	Techniques Now Available	Efficiency
1. Reducing peak temperature	Flue Gas Recirculation (FGR) Natural Gas Reburning (NGR) Low NOx Burners (LNB) Combustion Optimization Burners Out Of Service (BOOS) Over Fire Air (OFA) Less Excess Air (LEA) Inject Water or Steam Reduced Air Preheat	50-70%
2.Reducing residence time at peak temperature	Air Staging of Combustion Fuel Staging of Combustion Inject Steam	50-70%
3. Chemical reduction of NOx	Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction (SNCR) Fuel Reburning (FR) Low NOx Burners (LNB)	35-90%
4. Oxidation of NOx with subsequent absorption	Inject Oxidant Non-Thermal Plasma Reactor (NTPR)	60-80%
5. Removal of nitrogen	Ultra-Low Nitrogen Fuel	No Data
6. Using a sorbent	Sorbent In Combustion Chambers Sorbent In Ducts	60-90%

DRY BOTTOM BOILERS - TANGENTIALLY FIRED

Dry bottom pulverized coal, gas, or liquid fuel tangentially-fired boilers use jets from each corner of a furnace to inject fuel and combustion air in a swirl. The injected mix of fuel and combustion air forms a fireball in the center of the boiler. This firing configuration is used in medium sized utility and large industrial boilers. This combustion technique holds flame temperatures down (Method 1). In addition, chemical reduction of NOx (Method 3) is frequently used. NOx oxidation (Method 4) techniques may be used in the future. Sorbents (Method 6) are already used for some boilers. See Table 7 for NOx technologies used for dry bottom tangentially fired boilers.

Table 7: NOx technologies currently used for dry bottom tangentially fired boilers.

NOx Abatement Method	Techniques Now Available	Efficiency
1. Reducing peak temperature	Flue Gas Recirculation (FGR) Natural Gas Reburning (NGR) Over Fire Air (OFA) Less Excess Air (LEA) Inject Water or Steam Reduced Air Preheat	50-70%
2.Reducing residence time at peak temperature	Air Staging of Combustion Fuel Staging of Combustion Inject Steam	50-70%
3. Chemical reduction of NOx	Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction (SNCR) Fuel Reburning (FR)	35-90%
4. Oxidation of NOx with subsequent absorption	Non-Thermal Plasma Reactor (NTPR)	60-80%
5. Removal of nitrogen	Ultra-Low Nitrogen Fuel	No Data
6. Using a sorbent	Sorbent In Combustion Chambers Sorbent In Ducts	60-90%

WET BOTTOM (SLAG TAP) BOILERS

Wet bottom (slag tap) boilers use cyclone burners to create an intense flame. The flame is so hot that it melts ash, which then becomes slag that must be removed via a slag tap. These boilers are known to have higher NOx generation because combustion temperature is so high. As a result, this high temperature combustion technique is not widely used because the NOx concentration necessarily must be greater. Removal of non-fuel nitrogen as a reactant from the combustion process (Method 5) applies here. Reducing residence time at peak temperature, chemical

reduction of NOx, and NOx oxidation with absorption (Methods 2, 3 & 4) also apply to this combustion system. In addition, some slag tap boilers may be using sorbents (Method 6). There are recent reports that reducing peak temperature (Method 1) so that ash just melts has been used. See Table 8 for NOx technologies used for slag tap boilers.

Table 8: NOx technologies currently used for wet bottom (slag tap) boilers.

NOx Abatement Method	Techniques Now Available	Efficiency
1. Reducing peak temperature	Flue Gas Recirculation (FGR) Natural Gas Reburning (NGR) Over Fire Air (OFA) Less Excess Air (LEA) Inject Water or Steam Reduced Air Preheat	30-70%
2.Reducing residence time at peak temperature	Air Staging of Combustion Fuel Staging of Combustion Inject Steam	20-50%
3. Chemical reduction of NOx	Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction (SNCR) Fuel Reburning (FR)	35-90%
4. Oxidation of NOx with subsequent absorption	Non-Thermal Plasma Reactor (NTPR)	60-80%
5. Removal of nitrogen	Use Oxygen Instead Of Air Ultra-Low Nitrogen Fuel	No Data
6. Using a sorbent	Sorbent In Combustion Chambers Sorbent In Ducts	60-90%

FLUIDIZED BED

Fluidized bed combustion occurs in a bed of crushed coal that has air flowing upward through it to make coal particles behave like a fluid. Boiler pipes can be either submerged in the bed or exposed to the hot gases after they leave the bed. The fluidized bed is temperature controlled (Method 1). The bed also is a chemically reducing region in which available oxygen is consumed by carbon (Method 3) that reduces ionization of nitrogen. Excess air is injected (Method 2) over the fluidized bed to complete combustion of CO and other burnables. This allows for the addition of pulverized limestone (Method 6) to coal in the fluidized bed. Sulfur oxides then react with the limestone to form gypsum, a marketable product. Gypsum must be separated from the ash. As a result, NOx generation can be essentially limited to prompt NOx and fuel NOx. See Table 9 for NOx technologies used for fluidized bed combustion units.

Table 9: NOx techniques currently used for fluidized bed combustion.

NOx Abatement Method	Techniques Now Available	Efficiency
1. Reducing peak temperature	Flue Gas Recirculation (FGR) Natural Gas Reburning (NGR) Over Fire Air (OFA) Less Excess Air (LEA) Reduced Air Preheat	No Data
2.Reducing residence time at peak temperature	Inject Steam	No Data
3. Chemical reduction of NOx	Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction(SNCR) Fuel Reburning (FR)	35-90%
4. Oxidation of NOx with subsequent absorption	Non-Thermal Plasma Reactor (NTPR)	60-80%
5. Removal of nitrogen	Ultra-Low Nitrogen Fuel	No Data
6. Using a sorbent	Sorbent In Combustion Chambers Sorbent In Ducts	60-90%

STOKERS WITH TRAVELING GRATE

Stokers with traveling grate cause the coal to move as it burns. Thus, char combustion is in one zone while volatiles are liberated and combusted in another zone. These stokers are commonly used with industrial boilers that are smaller than utility boilers. Reducing peak temperature, chemical reduction of NOx, and sorbents (Methods 1, 3 & 6) usually are applied. Perhaps NOx oxidation (Method 4) also will apply in the future. See Table 10 for NOx technologies used for stokers with traveling grates.

STOKERS WITH SPREADERS

Stokers with spreaders throw coal over the grate in a controlled manner. Coal is crushed, but particles are typically larger than pulverized coal. Therefore, combustion of volatiles begins while coal is in flight and combustion of char occurs on the grate. This system is used with somewhat larger boilers than stokers with traveling grates. It can be used in power plants, but this combustion system is used mainly for industrial boilers. Like stokers with traveling grates, reducing peak temperature, chemical reduction of NOx, and sorbents (Methods 1, 3, and 6) usually are applied. Perhaps NOx oxidation (Method 4) also will apply in the future. See Table 11 for NOx technologies used for stokers with Spreader grates.

Table 10: NOx technologies currently used for stokers with traveling grates.

NOx Abatement Method	Technique Now Available	Efficiency
1. Reducing peak temperature	Flue Gas Recirculation (FGR) Natural Gas Reburning (NGR) Combustion Optimization Over Fire Air (OFA) Less Excess Air (LEA) Inject Water or Steam Reduced Air Preheat	35-50%
2.Reducing residence time at peak temperature	Air Staging of Combustion Fuel Staging of Combustion	50-70%
3. Chemical reduction of NOx	Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction (SNCR) Fuel Reburning (FR)	55-80%
4. Oxidation of NOx with subsequent absorption	Inject Oxidant Non-Thermal Plasma Reactor (NTPR)	60-80%
5. Removal of nitrogen	Ultra-Low Nitrogen Fuel	No Data
6. Using a sorbent	Sorbent In Combustion Chambers Sorbent In Ducts	60-90%

GAS TURBINES

Gas turbines use the Brayton Cycle with a burner to raise temperature of gas after compression and before expansion through the turbine. Turbines mainly use reducing peak temperature and reducing residence time (Methods 1 and 2) approaches to limit NOx emissions. Because addition of particles to air flow entering the turbine would accelerate erosion of turbine blades, sorbents (Method 6) could only be applied after the expansion in the turbine. NOx reduction (Method 3) has been used to treat exhaust gases. Many turbine operators claim that they use "good combustion practices" that do reduce the particles that produce visible emissions (which they equate with pollution), but say nothing about the NOx emissions which are not visible.

Cogeneration units use a gas turbine to generate electricity and provide preheated combustion air for a boiler. Gas turbine exhaust is typically 10-15% oxygen and can be used to provide combustion air for a low pressure boiler. That boiler can be used to provide steam for another turbine, a process heater, a space heater, or some combination of these. If a steam turbine is used to generate electricity, it may constrain what can be done. Sorbent particles can be introduced to a flow after it leaves a gas turbine in order to control NOx. There has also been some success in reducing NOx concentrations when burning biomass fuels in a boiler. See Table 12 for NOx technologies used for gas turbines.

Table 11: NOx technologies currently used for stokers with spreader grates.

NOx Abatement Method	Technique Now Available	Efficiency
1. Reducing peak temperature	Flue Gas Recirculation (FGR) Natural Gas Reburning (NGR) Low NOx Burners (LNB) Combustion Optimization Over Fire Air (OFA) Less Excess Air (LEA) Inject Water or Steam Reduced Air Preheat	50-65%
2.Reducing residence time at peak temperature	Air Staging of Combustion Fuel Staging of Combustion Inject Steam	50-65%
3. Chemical reduction of NOx	Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction (SNCR) Fuel Reburning (FR)	35-80%
4. Oxidation of NOx with subsequent absorption	Inject Oxidant Non-Thermal Plasma Reactor (NTPR)	60-80%
5. Removal of nitrogen	Ultra-Low Nitrogen Fuel	No Data
6. Using a sorbent	Sorbent In Combustion Chambers Sorbent In Ducts	60-90%

INTERNAL COMBUSTION RECIPROCATING ENGINES

Internal combustion engines use air-to-fuel ratio and ignition/injection timing to control maximum temperature and residence time. This can reduce the concentration of NOx that is generated by reducing peak temperature (Method 1). Valve timing adjustments can reduce residence time at peak temperature (Method 2) to control NOx formation. Chemical reduction of NOx (Method 3) is used in catalytic converters to reduce NOx to N_2. Some stationary engines use both Method 3 and NOx oxidation (Method 4). A non-thermal plasma reactor was developed for treatment of diesel exhaust, but is not yet marketed to our knowledge. A plasma ignition system allows greater freedom in the air-fuel ratio and the ignition timing of spark ignition engines. See Table 13 for NOx technologies used for stationary internal combustion engines.

WHAT DOES NOx ABATEMENT AND CONTROL COST?

The cost of NOx abatement and control has been changing rapidly with dramatic reductions in recent years. Table 14 gives the 1993 cost as given in the Alternative Control Techniques

Table 12: NOx technologies currently used for gas turbines.

NOx Abatement Method	Technique Now Available	Efficiency
1. Reducing peak temperature	Natural Gas Reburning (NGR) Low NOx Burners (LNB) Inject Water or Steam Reduced Air Preheat Catalytic Combustion	70-85%
2.Reducing residence time at peak temperature	Air Staging of Combustion Inject Steam	70-80%
3. Chemical reduction of NOx	Selective Catalytic Reduction (SCR) Selective Non-Catalytic Reduction (SNCR) Fuel Reburning (FR) Low NOx Burners (LNB)	70-90%
4. Oxidation of NOx with subsequent absorption	Non-Thermal Plasma Reactor (NTPR)	No Data
5. Removal of nitrogen	Ultra-Low Nitrogen Fuel	No Data
6. Using a sorbent	Sorbent In Ducts	60-90%

Table 13: NOx technologies currently used for stationary internal combustion engines.

NOx Abatement Method	Technique Now Available	Efficiency
1. Reducing peak temperature	Air/fuel Ratio Timing of Ignition/Type of Ignition Pre-Stratified Combustion	20-97%
2.Reducing residence time at peak temperature	Valve Timing	No Data
3. Chemical reduction of NOx	Selective Catalytic Reduction (SCR) Non-Selective Catalytic Reduction (NCSR)	80-90%
4. Oxidation of NOx with subsequent absorption	Non-Thermal Plasma Reactor (NTPR)	80-95%
5. Removal of nitrogen	Ultra-Low Nitrogen Fuel	No Data
6. Using a sorbent	Sorbent In Exhaust Ducts Adsorber in fixed Bed	60-90%

Table 14. 1993 Costs of NOx Controls

	Cost of NOx Controls in 1993 Dollars					
Control	Low -Cap.	High -Cap.	Low - Oper.	High -Oper.	Low	High
Device	$/MMBTU	$/MMBTU	$/MMBTU	$/MMBTU	$/ton	$/ton
LNB	650	8,300	340	1,500	240	4,300
LNB + FGR					650	7,630
SNCR	1,600	3,300	680	1,200	N/A	N/A
(1994 ESTIMATE)					700	1,300
SCR	2,400	20,000	1,500	5,800	1,810	10,900
(1994 ESTIMATE)					500	2,800

Document NOx Emissions from Industrial/Commercial/Institutional Boilers (EPA 453/R-94-022).
The EPA Region III Low-NOx Control Technology Study in 1994 said that low-NOx burners had both beneficial effects on operating costs and detrimental effects on the burners, their life expectancy, and the boilers in which they were installed. Coal quality and some boiler designs caused NOx to remain high even after low-NOx burners were in place. Capital costs ranged from $1.91 to $54.24 per kW. Operating costs ranged from $-23,000 (a profit) to $1,113,750 per year. Thus, no reliable cost estimates could be obtained regarding low-NOx burner operation. Coal quality, boiler capacity, and burner design were among the variables influencing this cost. Many plants could not even give an estimate. SNCR cost between $700 and $1,300 per ton of NOx reduced. SCR cost between $500 and $2,800 per ton of NOx reduced.[25] However, cost per ton of NOx removed for all technologies is apparently becoming smaller.

These costs vary by control technique; type of fuel; grade of fuel; size of boiler, engine or turbine; type of boiler, or turbine; and other factors. Other costs were also changing with time. Therefore you need to examine the costs of these NOx control technologies for a specific application and at a particular time.

These preliminary cost estimates will also be further reduced as operating experience is gained, competition sharpens, and design iterations eliminate the high-maintenance or life-shortening features. Confidence in this view of the future is based upon reports that some users of low-NOx burners had already seen in 1994 that operating costs could be reduced to make the changeover yield a net profit. SCR and SNCR costs may also have declined further, since there is now competition for these technologies.

This analysis was supported by 1997 cost figures. These are presented in Table 15. This table is from the Analyzing Electric Power Generation Under the CAAA [26]. It appears that competition and improved designs are still driving the costs downward. The Table was presented in that publication and is presented here for your convenience.

Table 15. 1997 Costs of NOx Controls

Analyzing Electric Power Generation Under the CAAA -- Cost Estimates[26]					
Boiler Type	Control Type	Capital Cost	Fixed O & M	Variable O& M	% Control
		$/kW	$/kW/yr	mils/kWh	
Wall Fired	LNB w/o OFA	16.8	0.25	0.05	67.5
Wall Fired	LNB w/ OFA	22.8	0.35	0.07	67.5
Tang-Fired	LNB w/ OFA	32.3	0.49	0	47.3
Tang-Fired LNB w/ SOFA		34.7	0.53	0	52.3
Tang Fired LNB w/ BOFA		46.7	0.71	0.02	57.3
Cell Burners	Non Plug-In Comb. Ctl.	22.8	0.34	0.07	60
Cyclone	Coal Reburning	70.7	1.07	0.25	50
Wet Bottom	NOx Comb. Ctl.	9.6	0.14	0.05	50
Vert. Fired	NOx Comb. Ctl.	10.8	0.17	0.05	40
	SCR -Low NOx Rate	69.7	6.12	0.24	70
	SCR- High NOx Rate	71.8	6.38	0.4	80
	SNCR-Low NOx Rate	16.6	0.24	0.82	40
	SNCR-Cyclone	9.6	0.14	1.27	35
	SNCR-High NOx Rate	19	0.29	0.88	35
	Nat.Gas Reburn-Low	32.4	0.49		40
	Nat.Gas Reburn-High	32.4	0.49		50

Note that in Table 8 the following acronyms are used:

LNB is low-NOx burner
OFA is closed coupled overfire air
SOFA is separate over fire air
BOFA is both close coupled and over fire air
Comb. Ctl. is combined controls

The Institute of Clean Air Companies also suggests that in 1999 SCR will cost $50 - $80 per kW for retrofit to units, which relates to $400-$1800 per ton of NOx that is destroyed.[34] Their cost estimate for SNCR ranges from $5-$15 per kW, which relates to $400-$2000 per ton of NOx that is destroyed.[35] Cost-effectiveness does not correlate with boiler capacity alone - other variables such as type and quality of fuel, type of boiler, SNCR/SCR design, etc enter into the analysis.

While the "Performance of Selective Catalytic Reduction on Coal-fired Steam Generating Units" study was for Germany, it cited a recent cost range for SCR from $52 to $77 per kW with retrofit units tending to have lower costs. Thus, the costs in Germany were very similar to costs in the U.S.A., except that retrofit costs usually are greater in the United States.

Table 16, Unit Costs for NOx control Technologies for Non-Utility Stationary Sources, is from the report "Ozone Transport Rulemaking Non-Electricity Generating Unit Cost Analysis." The report was prepared for EPA by the Pechan-Avanti Group. It indicates efficiencies and cost estimates for various NOx technologies for the year 2007. This appears to be a conservative estimate of efficiency and cost. Efficiencies indicated in the table tend to be lower than currently demonstrated efficiencies. Costs were based on historical information and, therefore, should be high estimates because NOx technology costs appear to be declining over time. The table was included here to indicate the relative efficiency and cost of NOx technologies for specific types of combustion systems.

The Alternative Control Techniques Document NOx Emissions from Stationary Reciprocating Internal Combustion Engines contains cost algorithms for the pollution prevention techniques and control technology applied to internal reciprocating engines. Costs for NOx elimination run from $250/ton to $1,300/ton for engines larger than 1,000 horsepower. For smaller engines the cost runs from $400/ton to over $3,500/ton.

ARE THESE METHODS SUFFICIENT?

YES, these methods are sufficient to meet the present goal of reducing NOx emissions 2 million tons below 1980 emissions.[47] The goal appears to be set at a level that can be achieved based on the state of NOx technology in 1996. However, we will have to see whether achieving our present goal provides the needed relief. A still more stringent set of standards may become necessary at sometime in the future.

As a high-technology nation and with a large urban and suburban population, we depend on automobiles, buses, airplanes, railroads, and trucks for transportation. We also depend upon electric power for computers, lights, air conditioning, and commerce. Therefore, we seem caught in a dilemma, for, while we depend on transportation, vehicles produce most of our NOx. While we also consume electric power as part of our market economy, electric power generation also generates over 40% of our NOx from stationary sources in 1995.[34]

We also need to generate less NOx without regard to the ionization level of the nitrogen. In 1999, we are currently not capable of doing that. Therefore, we must do the best that we can,

Table 16: Unit Costs for NO_x Control Technologies for Non-Utility Stationary Sources

Source Type/Fuel Type	Control Technology	Percent Reduction (%)	Ozone Season Cost Effectiveness ($1990/ton) Small*	Large*
ICI Boilers - Coal/Wall	SNCR	40	1,870	1,380
ICI Boilers - Coal/Wall	LNB	50	3,490	2,600
ICI Boilers - Coal/Wall	SCR	70	2,910	2,450
ICI Boilers - Coal/FBC	SNCR - Urea	75	1,220	910
ICI Boilers - Coal/Stoker	SNCR	40	1,810	1,350
ICI Boilers - Coal/Cyclone	SNCR	35	1,480	1,110
ICI Boilers - Coal/Cyclone	Coal Reburn	50	3,730	710
ICI Boilers - Coal/Cyclone	NGR	55	3,730	710
ICI Boilers - Coal/Cyclone	SCR	80	1,840	1,560
ICI Boilers - Residual Oil	LNB	50	940	1,020
ICI Boilers - Residual Oil	SNCR	50	5,600	1,950
ICI Boilers - Residual Oil	LNB + FGR	60	2,670	920
ICI Boilers - Residual Oil	SCR	80	3,460	1,840
ICI Boilers - Distillate Oil	LNB	50	2,810	4,950
ICI Boilers - Distillate Oil	SNCR	50	10,080	3,520
ICI Boilers - Distillate Oil	LNB + FGR	60	5,960	1,810
ICI Boilers - Distillate Oil	SCR	80	6,480	3,460
ICI Boilers - Natural Gas	LNB	50	1,950	1,560
ICI Boilers - Natural Gas	SNCR	50	8,400	2,930
ICI Boilers - Natural Gas	LNB + FGR	60	6,110	1,420
ICI Boilers - Natural Gas	OT + WI	65	1,620	760
ICI Boilers - Natural Gas	SCR	80	5,190	2,770
ICI Boilers - Wood/Bark/Stoker	SNCR - Urea	55	2,090	1,430
ICI Boilers - Wood/Bark/FBC	SNCR - Ammonia	55	1,660	1,210
ICI Boilers - MSW/Stoker	SNCR - Urea	55	2,610	1,830
ICI Boilers - Process Gas	LNB	50	1,950	1,560
ICI Boilers - Process Gas	LNB + FGR	60	6,110	1,420
ICI Boilers - Process Gas	OT + WI	65	1,620	760
ICI Boilers - Process Gas	SCR	80	4,990	2,570
ICI Boilers - Coke	SNCR	40	1,870	1,380
ICI Boilers - Coke	LNB	50	3,490	2,600
ICI Boilers - Coke	SCR	70	2,910	2,450
ICI Boilers - LPG	LNB	50	2,810	4,950
ICI Boilers - LPG	SNCR	50	10,000	3,440
ICI Boilers - LPG	LNB + FGR	60	5,960	1,810
ICI Boilers - LPG	SCR	80	6,240	3,220
ICI Boilers - Bagasse	SNCR - Urea	55	2,090	1,430
ICI Boilers - Liquid Waste	LNB	50	940	1,020
ICI Boilers - Liquid Waste	SNCR	50	5,560	1,910
ICI Boilers - Liquid Waste	LNB + FGR	60	2,670	920
ICI Boilers - Liquid Waste	SCR	80	3,320	1,710
Internal Combustion Engines - Oil	IR	25	1,840	1,160

Source Type/Fuel Type	Control Technology	Percent Reduction (%)	Ozone Season Cost Effectiveness ($1990/ton) Small*	Large*
Internal Combustion Engines - Oil	SCR	80	4,690	1,850
Internal Combustion Engines - Gas	IR	20	2,430	1,320
Internal Combustion Engines - Gas	AF RATIO	20	3,730	900
Internal Combustion Engines - Gas	AF + IR	30	3,430	1,080
Internal Combustion Engines - Gas	L-E (Medium Speed)	87	890	N/A
Internal Combustion Engines - Gas	L-E (Low Speed)	87	4,000	1,500
Internal Combustion Engines - Gas	SCR	90	5,547	1,075
IC Engines - Gas, Diesel, LPG	IR	25	1,840	1,160
IC Engines - Gas, Diesel, LPG	SCR	80	4,690	1,850
Gas Turbines - Oil	Water Injection	68	3,080	1,540
Gas Turbines - Oil	SCR + Water Injection	90	4,240	1,860
Gas Turbines - Natural Gas	Water Injection	76	3,590	1,750
Gas Turbines - Natural Gas	Steam Injection	80	2,490	1,190
Gas Turbines - Natural Gas	LNB	84	1,170	240
Gas Turbines - Natural Gas	SCR + LNB	94	4,850	1,140
Gas Turbines - Natural Gas	SCR + Steam Injection	95	3,750	1,570
Gas Turbines - Natural Gas	SCR + Water Injection	95	5,040	2,060
Gas Turbines - Jet Fuel	Water Injection	68	3,080	1,540
Gas Turbines - Jet Fuel	SCR + Water Injection	90	4,240	1,860
Process Heaters - Distillate Oil	LNB	45	8,290	2,320
Process Heaters - Distillate Oil	LNB + FGR	48	10,130	4,000
Process Heaters - Distillate Oil	SNCR	60	6,210	3,230
Process Heaters - Distillate Oil	ULNB	74	5,110	1,450
Process Heaters - Distillate Oil	SCR	75	18,970	12,520
Process Heaters - Distillate Oil	LNB + SNCR	78	7,160	3,630
Process Heaters - Distillate Oil	LNB + SCR	92	18,770	10,910
Process Heaters - Residual Oil	LNB + FGR	34	8,330	3,290
Process Heaters - Residual Oil	LNB	37	6,010	1,690
Process Heaters - Residual Oil	SNCR	60	3,730	2,050
Process Heaters - Residual Oil	ULNB	73	3,080	860
Process Heaters - Residual Oil	LNB + SNCR	75	4,730	2,510
Process Heaters - Residual Oil	SCR	75	10,560	7,170
Process Heaters - Residual Oil	LNB + SCR	91	11,170	6,550
Process Heaters - Natural Gas	LNB	50	5,250	4,290
Process Heaters - Natural Gas	LNB + FGR	55	7,610	5,890
Process Heaters - Natural Gas	SNCR	60	5,560	3,740
Process Heaters - Natural Gas	ULNB	75	3,580	2,870
Process Heaters - Natural Gas	SCR	75	24,840	16,760
Process Heaters - Natural Gas	LNB + SNCR	80	6,960	5,080
Process Heaters - Natural Gas	LNB + SCR	88	23,880	16,500
Process Heaters - Process Gas	LNB	50	5,250	4,290
Process Heaters - Process Gas	LNB + FGR	55	7,610	5,890
Process Heaters - Process Gas	SNCR	60	5,560	3,740
Process Heaters - Process Gas	ULNB	75	3,580	2,870
Process Heaters - Process Gas	SCR	75	24,840	16,760
Process Heaters - Process Gas	LNB + SNCR	80	6,960	5,080
Process Heaters - Process Gas	LNB + SCR	88	23,880	16,500

Source Type/Fuel Type	Control Technology	Percent Reduction (%)	Ozone Season Cost Effectiveness ($1990/ton) Small*	Large*
Process Heaters - LPG	LNB	45	8,290	2,320
Process Heaters - LPG	LNB + FGR	48	10,130	4,000
Process Heaters - LPG	SNCR	60	6,210	3,230
Process Heaters - LPG	ULNB	74	5,110	1,450
Process Heaters - LPG	SCR	75	18,970	12,520
Process Heaters - LPG	LNB + SNCR	78	7,160	3,630
Process Heaters - LPG	LNB + SCR	92	18,770	10,910
Process Heaters - Other Fuel	LNB + FGR	34	8,330	3,290
Process Heaters - Other Fuel	LNB	37	6,010	1,690
Process Heaters - Other Fuel	SNCR	60	3,730	2,050
Process Heaters - Other Fuel	ULNB	73	3,080	860
Process Heaters - Other Fuel	LNB + SNCR	75	4,730	2,510
Process Heaters - Other Fuel	SCR	75	10,560	7,170
Process Heaters - Other Fuel	LNB + SCR	91	11,170	6,550
Adipic Acid Manufacturing	Thermal Reduction	81	1,000	1,000
Adipic Acid Manufacturing	Extended Absorption	86	210	210
Nitric Acid Manufacturing	Extended Absorption	95	840	840
Nitric Acid Manufacturing	SCR	97	1,010	1,010
Nitric Acid Manufacturing	SNCR	98	940	940
Glass Manufacturing - Container	Electric Boost	10	17,050	17,050
Glass Manufacturing - Container	Cullet Preheat	25	2,240	2,240
Glass Manufacturing - Container	LNB	40	4,040	4,040
Glass Manufacturing - Container	SNCR	40	3,320	3,320
Glass Manufacturing - Container	SCR	75	4,550	4,550
Glass Manufacturing - Container	OXY-Firing	85	10,960	10,960
Glass Manufacturing - Flat	Electric Boost	10	5,540	5,540
Glass Manufacturing - Flat	LNB	40	1,660	1,660
Glass Manufacturing - Flat	SNCR	40	1,380	1,380
Glass Manufacturing - Flat	SCR	75	1,490	1,490
Glass Manufacturing - Flat	OXY-Firing	85	4,530	4,530
Glass Manufacturing - Pressed	Electric Boost	10	20,910	20,910
Glass Manufacturing - Pressed	Cullet Preheat	25	1,930	1,930
Glass Manufacturing - Pressed	LNB	40	3,570	3,570
Glass Manufacturing - Pressed	SNCR	40	3,080	3,080
Glass Manufacturing - Pressed	SCR	75	5,170	5,170
Glass Manufacturing - Pressed	OXY-Firing	85	9,310	9,310
Cement Manufacturing - Dry	Mid-Kiln Firing	30	1,110	1,110
Cement Manufacturing - Dry	LNB	30	1,340	1,340
Cement Manufacturing - Dry	SNCR - Urea Based	50	1,280	1,280
Cement Manufacturing - Dry	SNCR - NH3 Based	50	1,490	1,490
Cement Manufacturing - Dry	SCR	80	6,850	6,850
Cement Manufacturing - Wet	Mid-Kiln Firing	30	1,010	1,010
Cement Manufacturing - Wet	LNB	30	1,260	1,260
Cement Manufacturing - Wet	SCR	80	5,840	5,840
Iron & Steel Mills - Reheating	LEA	13	3,160	3,160
Iron & Steel Mills - Reheating	LNB	66	720	720
Iron & Steel Mills - Reheating	LNB + FGR	77	900	900

Source Type/Fuel Type	Control Technology	Percent Reduction (%)	Ozone Season Cost Effectiveness ($1990/ton) Small*	Large*
Iron & Steel Mills - Annealing	LNB	50	1,350	1,350
Iron & Steel Mills - Annealing	LNB + FGR	60	1,790	1,790
Iron & Steel Mills - Annealing	SNCR	60	3,130	3,130
Iron & Steel Mills - Annealing	LNB + SNCR	80	3,460	3,460
Iron & Steel Mills - Annealing	SCR	85	8,490	8,490
Iron & Steel Mills - Annealing	LNB + SCR	90	9,070	9,070
Iron & Steel Mills - Galvanizing	LNB	50	1,170	1,170
Iron & Steel Mills - Galvanizing	LNB + FGR	60	1,370	1,370
Municipal Waste Combustors	SNCR	45	2,140	2,140
Medical Waste Incinerators	SNCR	45	8,570	8,570
Space Heaters - Distillate Oil	LNB	50	2,810	4,950
Space Heaters - Distillate Oil	SNCR	50	10,000	3,440
Space Heaters - Distillate Oil	LNB + FGR	60	5,960	1,810
Space Heaters - Distillate Oil	SCR	80	6,240	3,220
Space Heaters - Natural Gas	LNB	50	1,950	1,560
Space Heaters - Natural Gas	SNCR	50	8,330	2,860
Space Heaters - Natural Gas	LNB + FGR	60	6,110	1,420
Space Heaters - Natural Gas	OT + WI	65	1,620	760
Space Heaters - Natural Gas	SCR	80	4,990	2,570
Ammonia - NG-Fired Reformers	LNB	50	1,950	1,560
Ammonia - NG-Fired Reformers	SNCR	50	8,330	2,860
Ammonia - NG-Fired Reformers	LNB + FGR	60	6,110	1,420
Ammonia - NG-Fired Reformers	OT + WI	65	1,620	760
Ammonia - NG-Fired Reformers	SCR	80	4,990	2,570
Ammonia - Oil-Fired Reformers	LNB	50	940	1,020
Ammonia - Oil-Fired Reformers	SNCR	50	5,560	1,910
Ammonia - Oil-Fired Reformers	LNB + FGR	60	2,670	920
Ammonia - Oil-Fired Reformers	SCR	80	3,320	1,710
Lime Kilns	Mid-Kiln Firing	30	1,110	1,110
Lime Kilns	LNB	30	1,340	1,340
Lime Kilns	SNCR - Urea Based	50	1,280	1,280
Lime Kilns	SNCR - NH3 Based	50	1,490	1,490
Lime Kilns	SCR	80	6,850	6,850
Comm./Inst. Incinerators	SNCR	45	2,140	2,140
Indust. Incinerators	SNCR	45	2,140	2,140
Sulfate Pulping - Recovery Furnaces	LNB	50	1,950	1,560
Sulfate Pulping - Recovery Furnaces	SNCR	50	8,330	2,860
Sulfate Pulping - Recovery Furnaces	LNB + FGR	60	6,110	1,420
Sulfate Pulping - Recovery Furnaces	OT + WI	65	1,620	760
Sulfate Pulping - Recovery Furnaces	SCR	80	4,990	2,570
Ammonia Prod; Feedstock Desulfurization	LNB + FGR	60	6,110	1,420
Plastics Prod-Specific; (ABS) Resin	LNB + FGR	55	7,610	5,890
Starch Mfg; Combined Operations	LNB + FGR	55	7,610	5,890

Source Type/Fuel Type	Control Technology	Percent Reduction (%)	Ozone Season Cost Effectiveness ($1990/ton) Small*	Large*
By-Product Coke Mfg; Oven Underfiring	SNCR	60	3,130	3,130
Pri Cop Smel; Reverb Smelt Furn	LNB + FGR	60	1,790	1,790
Iron Prod; Blast Furn; Blast Htg Stoves	LNB + FGR	77	900	900
Steel Prod; Soaking Pits	LNB + FGR	60	1,790	1,790
Fuel Fired Equip; Process Htrs; Pro Gas	LNB + FGR	55	7,610	5,890
Sec Alum Prod; Smelting Furn/Reverb	LNB	50	1,350	1,350
Steel Foundries; Heat Treating Furn	LNB	50	1,350	1,350
Fuel Fired Equip; Furnaces; Natural Gas	LNB	50	1,350	1,350
Asphaltic Conc; Rotary Dryer; Conv Plant	LNB	50	5,250	4,290
Ceramic Clay Mfg; Drying	LNB	50	5,250	4,290
Coal Cleaning-Thrml Dryer; Fluidized Bed	LNB	50	3,490	2,600
Fbrglass Mfg; Txtle-Type Fbr; Recup Furn	LNB	40	4,040	4,040
Sand/Gravel; Dryer	LNB + FGR	55	7,610	5,890
Fluid Cat Cracking Units; Cracking Unit	LNB + FGR	55	7,610	5,890
Conv Coating of Prod; Acid Cleaning Bath	LNB	50	5,250	4,290
Natural Gas Prod; Compressors	SCR	20	5,547	1,075
In-Process; Bituminous Coal; Cement Kiln	SNCR - urea based	50	1,280	1,280
In-Process; Bituminous Coal; Lime Kiln	SNCR - urea based	50	1,280	1,280
In-Process Fuel Use;Bituminous Coal; Gen	SNCR	40	1,420	1,060
In-Process Fuel Use; Residual Oil; Gen	LNB	37	6,010	1,690
In-Process Fuel Use; Natural Gas; Gen	LNB	50	5,250	4,290
In-Proc;Process Gas;Coke Oven/Blast Furn	LNB + FGR	55	7,610	5,890
In-Process; Process Gas; Coke Oven Gas	LNB	50	5,250	4,290
Surf Coat Oper;Coating Oven Htr;Nat Gas	LNB	50	5,250	4,290
Solid Waste Disp;Gov;Other Incin;Sludge	SNCR	45	2,140	2,140

NOTE: *Small source cost per ton values are used to estimate control costs for all sources with 1995 NO_x emissions below 1 ton per day. If the ozone season daily 1995 baseline NO_x value is 1 ton or more, the cost per ton value for large sources is used.
N/A = not applicable. The population of medium speed gas-fired IC engines are all considered small.

and hope that we can endure while looking for the discovery and cost-reduction of the "better technology" that is capable of meeting the goal of sustainability. The reference literature suggests that the leading edge of pollution prevention and control technology in 1999 is capable of about 94%-99% control of NOx or 1 ppm-5 ppm of NOx.[27,28]

As we all know, the leading edge technology always costs more because engineering has not yet shifted from feasibility to cost-reduction, and competition in the technology is not fully developed. Therefore, we can expect technology to be more affordable with time and to also improve its capability. We should expect to see the goal change with time as the technology advances, and as the achievable goal becomes both more stringent and more economically feasible. At one time, the capabilities that we now have seemed beyond imagining, and the costs seemed prohibitive. We live in an interesting time when the NOx pollution prevention, abatement, and control technology is becoming more capable and more affordable.

CONCLUSIONS

1. Different fuels require different combustion, abatement and control techniques. Different coals have a varying content of volatile ingredients. The nitrogen content of fuel is important, as are the content of sulfur, lead, mercury and other contaminants. Ultra-low nitrogen content fuels have been developed and are already cost competitive. Thus, we can achieve some control of NOx from the lowered concentration of nitrogen in the fuel without investing in changed burner designs.[29]

2. The design of the boiler, internal combustion engine, or gas turbine has a major effect on the operation. NOx formation tends to increase with an increase in boiler capacity, because larger boilers tend to have more intense combustion with higher combustion temperatures and longer residence time for flue gases. The same appears to be true of engines and turbines.

3. Staging of the combustion is implicit in several pollution prevention techniques. Tandem application (or use of hybrid control technology) of NOx control techniques (first SNCR, then SCR in the duct, and then sorption before the ESP which is referred to as "polishing") have been used to achieve an overall reduction of 90+% in NOx and 80% in SOx, even without using low-NOx burners to lower NOx generation.

4. Combustion of natural gas and petroleum distillates can be controlled in much the same way as pulverized coal. The major differences between coal and natural gas or oil are that gas and oil: (1) generally are lower in sulfur and ash; (2) usually are lower in nitrogen; and (3) probably are lower in lead and mercury. Thus, gas and oil do not deactivate a catalyst used in Selective Catalytic Reduction (SCR) at the same rate that coal or semi-solid fuels do.

5. The semi-solid petroleum products can actually have higher levels of sulfur, nitrogen and other impurities than coal. They do not have as much char or ash as coal, but have more than the lighter distillates.

6. We should expect the declining cost trend of control technology to continue as operating experience is gained, firing techniques are adapted to fuels, design flaws are corrected, and new designs appear. We should expect to see costs become less as they are driven down by competition between suppliers of successful technologies.

7. NOx control technology appears capable of more than just meeting EPA's present goal and this should provide emission credits that can be traded to those firms that choose to continue emitting poorly controlled emissions. The sale of these credits by those that over-corrected for the present goal should further offset any net costs in adopting these control technologies.

8. Commercially available NOx control systems are already available. The availability of these technologies was part of the basis of the recent NOx SIP Call and Title IV regulations.

9. There has been an economic incentive to make combustion more efficient and to innovate ways to control nitrogen oxides. However, the amount of time and money that must be invested for a full-scale test of a strategy is significant. Acceptance requires that a technology be tried and succeed before a larger scale test is even contemplated. This delays acceptance of improved techniques.

10. There seems to be no control technology which is clearly superior for all combustion systems, boilers, engines, or fuels. Lacking a clear winner, one must select fuels and control technology either from among those already proven, or from a growing number of new and promising ideas.

11. The end of the search for control technologies is not yet in sight, and the search must continue. Past research must of necessity give ambivalent answers, because there are so many conflicting factors. However, at under $150 per ton of NOx prevented and with up to 80% control efficiency, the low-NOx burner, where applicable, appears to be among the least expensive emission control technologies. SCR is more expensive, but can obtain up to 94% control efficiency. SNCR can be adopted without the initial cost of catalyst, although it is somewhat less effective. LNB, SCR and SNCR are all viable technologies across a wide spectrum of applications.

12. Research and development will have to continue to seek more effective answers and try to balance them against cost and efficiency. The cost will decrease as technology advances, operating experience is gained, competition becomes sharper, design flaws are corrected, and better designs become available. Reliability can only be gained with time. Cost will be reduced with time and experience. We also must expect that the level of pollution prevention and control technology effectiveness will improve with time.

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16. ABSTRACT

The purpose of this document is to educate people about nitrogen oxides, how they are formed, the danger that they represent, and how emissions can be controlled. This knowledge is needed to make an informed choice of the control technology that is to be used.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
nitrous oxide, nitric oxide, nitrogen dioxide, dinitrogen pentoxide, nitrous acid, nitric acid, ozone, volatile organic compounds, VOC, generation, pollution prevention, control technology, control technologies, emission control, acid rain, combustion, boilers, gas turbines, internal combustion engines, cost of emission controls, air pollution	air pollution control technology, combustion, pollution prevention, nitrogen oxides, boilers, internal combustion engines, diesel engines	

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Annexe C TAUX D'ÉMISSIONS DES SUBSTANCES MODÉLISÉES

TABLEAU C1 - TAUX D'ÉMISSIONS DES SOURCES VISÉES POUR LE SCÉNARIO PRÉ-PROJET

No Source	Description	Substance	Taux d'émission	Taux d'émission annualisé
3	**Poste désemballage "labpacks"**	Acétate de butyle	9,06E-05	5,38E-06
		Acétate d'éthyle	8,73E-03	5,18E-04
		Acétate de méthyle	7,98E-04	4,74E-05
		Acétate de propyle	5,85E-04	3,47E-05
		Acétate de propylène glycol méthyle éther	3,76E-04	2,23E-05
		Acétone	5,06E-02	3,00E-03
		Acétonitrile	2,33E-03	1,38E-04
		Alcool éthylique	8,90E-03	5,28E-04
		Alcool isobutylique	2,13E-04	1,26E-05
		Alcool méthylique	1,56E-02	9,25E-04
		Benzène	1,67E-03	9,92E-05
		n-Butanol	4,16E-05	2,47E-06
		2-Butoxyéthanol	4,40E-06	2,61E-07
		sec-Butylbenzène	4,35E-05	2,58E-06
		Chloroforme	2,16E-02	1,28E-03
		3-Chlorophénol	2,25E-09	1,33E-10
		4-Chlorophénol	3,52E-10	2,09E-11
		p-Chlorotrifluorométhyl benzène	1,62E-05	9,62E-07
		Chlorure de méthylène	6,72E-02	3,99E-03
		o-Crésol	2,19E-08	1,30E-09
		m-Crésol	1,18E-08	6,98E-10
		p-Crésol	2,35E-07	1,40E-08
		Cyclohexane	2,91E-03	1,73E-04
		1,2-Dichlorobenzène	3,62E-05	2,15E-06
		1,3-Dichlorobenzène	5,76E-05	3,42E-06
		2,4+2,5-Dichlorophénol	4,13E-10	2,45E-11
		2,6-Dichlorophénol	4,54E-09	2,69E-10
		3,5-Dichlorophénol	1,89E-10	1,12E-11
		2,4-Diméthylphénol	2,20E-06	1,31E-07
		Éthylbenzène	6,41E-04	3,80E-05
		Éther de méthyle et de butyle tertiaire	1,78E-02	1,06E-03
		Heptane	1,43E-02	8,48E-04
		Isopropanol	4,66E-03	2,76E-04
		Isopropylbenzène (cumène)	1,05E-04	6,26E-06
		p-Isopropyltoluène (para-cymène)	3,78E-05	2,25E-06
		Méthyle n-amyl cétone	1,19E-05	7,09E-07
		Méthyl cyclohexane	8,56E-04	5,08E-05
		Méthyl éthyl cétone	2,95E-02	1,75E-03
		Méthyl isobutyle cétone	3,86E-03	2,29E-04
		Naphtalène	2,03E-06	1,20E-07
		4-Nitrophénol	2,16E-10	1,28E-11
		Pentachlorobenzène	5,71E-12	3,39E-13
		Pentachlorophénol	3,75E-11	2,23E-12
		Phénol	3,83E-07	2,28E-08
		n-Propanol	1,74E-04	1,03E-05
		n-Propylbenzène	8,00E-05	4,75E-06
		Propylène glycol monométhyléther	5,19E-05	3,08E-06
		1,2,3,4-Tétrachlorobenzène	1,56E-10	9,23E-12
		1,2,3,5 et 1,2,4,5-Tétrachlorobenzènes	8,40E-10	4,99E-11
		Tétrachloroéthylène	5,47E-04	3,25E-05
		2,3,4,6-Tétrachlorophénol	1,37E-10	8,13E-12
		Tétrahydro furanne	1,33E-03	7,88E-05
		Toluène	4,83E-03	2,87E-04
		1,2,4-Trichlorobenzène	3,13E-09	1,86E-10
		Trichloroéthène (Trichloroéthylène)	1,71E-03	1,01E-04
		1,2,4-Triméthylbenzène	7,08E-05	4,20E-06
		1,3,5-Triméthylbenzène	5,81E-05	3,45E-06
		Xylènes	2,12E-03	1,26E-04
		Acide chlorhydrique	2,02E-02	9,58E-04
		Acide nitrique	5,17E-02	2,46E-03
		Acide sulfurique	6,53E-08	3,10E-09
4	**Poste désemballage "labpacks"**	Acétate de butyle	9,06E-05	5,38E-06
		Acétate d'éthyle	8,73E-03	5,18E-04
		Acétate de méthyle	7,98E-04	4,74E-05
		Acétate de propyle	5,85E-04	3,47E-05

TABLEAU C1 - TAUX D'ÉMISSIONS DES SOURCES VISÉES POUR LE SCÉNARIO PRÉ-PROJET

No Source	Description	Substance	Taux d'émission	Taux d'émission annualisé
		Acétate de propylène glycol méthyle éther	3,76E-04	2,23E-05
		Acétone	5,06E-02	3,00E-03
		Acétonitrile	2,33E-03	1,38E-04
		Alcool éthylique	8,90E-03	5,28E-04
		Alcool isobutylique	2,13E-04	1,26E-05
		Alcool méthylique	1,56E-02	9,25E-04
		Benzène	1,67E-03	9,92E-05
		n-Butanol	4,16E-05	2,47E-06
		2-Butoxyéthanol	4,40E-06	2,61E-07
		sec-Butylbenzène	4,35E-05	2,58E-06
		Chloroforme	2,16E-02	1,28E-03
		3-Chlorophénol	2,25E-09	1,33E-10
		4-Chlorophénol	3,52E-10	2,09E-11
		p-Chlorotrifluorométhyl benzène	1,62E-05	9,62E-07
		Chlorure de méthylène	6,72E-02	3,99E-03
		o-Crésol	2,19E-08	1,30E-09
		m-Crésol	1,18E-08	6,98E-10
		p-Crésol	2,35E-07	1,40E-08
		Cyclohexane	2,91E-03	1,73E-04
		1,2-Dichlorobenzène	3,62E-05	2,15E-06
		1,3-Dichlorobenzène	5,76E-05	3,42E-06
		2,4+2,5-Dichlorophénol	4,13E-10	2,45E-11
		2,6-Dichlorophénol	4,54E-09	2,69E-10
		3,5-Dichlorophénol	1,89E-10	1,12E-11
		2,4-Diméthylphénol	2,20E-06	1,31E-07
		Éthylbenzène	6,41E-04	3,80E-05
		Éther de méthyle et de butyle tertiaire	1,78E-02	1,06E-03
		Heptane	1,43E-02	8,48E-04
		Isopropanol	4,66E-03	2,76E-04
		Isopropylbenzène (cumène)	1,05E-04	6,26E-06
		p-Isopropyltoluène (para-cymène)	3,78E-05	2,25E-06
		Méthyle n-amyl cétone	1,19E-05	7,09E-07
		Méthyl cyclohexane	8,56E-04	5,08E-05
		Méthyl éthyl cétone	2,95E-02	1,75E-03
		Méthyl isobutyle cétone	3,86E-03	2,29E-04
		Naphtalène	2,03E-06	1,20E-07
		4-Nitrophénol	2,16E-10	1,28E-11
		Pentachlorobenzène	5,71E-12	3,39E-13
		Pentachlorophénol	3,75E-11	2,23E-12
		Phénol	3,83E-07	2,28E-08
		n-Propanol	1,74E-04	1,03E-05
		n-Propylbenzène	8,00E-05	4,75E-06
		Propylène glycol monométhyléther	5,19E-05	3,08E-06
		1,2,3,4-Tétrachlorobenzène	1,56E-10	9,23E-12
		1,2,3,5 et 1,2,4,5-Tétrachlorobenzènes	8,40E-10	4,99E-11
		Tétrachloroéthylène	5,47E-04	3,25E-05
		2,3,4,6-Tétrachlorophénol	1,37E-10	8,13E-12
		Tétrahydro furanne	1,33E-03	7,88E-05
		Toluène	4,83E-03	2,87E-04
		1,2,4-Trichlorobenzène	3,13E-09	1,86E-10
		Trichloroéthène (Trichloroéthylène)	1,71E-03	1,01E-04
		1,2,4-Triméthylbenzène	7,08E-05	4,20E-06
		1,3,5-Triméthylbenzène	5,81E-05	3,45E-06
		Xylènes	2,12E-03	1,26E-04
		Acide chlorhydrique	2,02E-02	9,58E-04
		Acide nitrique	5,17E-02	2,46E-03
		Acide sulfurique	6,53E-08	3,10E-09
6	**Poste de percement de cannettes aérosols**	Acétate de butyle	1,22E-02	1,16E-03
		Acétone	2,43E-02	2,31E-03
		Éthylbenzène	4,06E-04	3,85E-05
		Toluène	1,01E-02	9,63E-04
		Xylène	2,03E-03	1,93E-04
8A	**Ouverture Sud du dôme (abri)**	Acétate de butyle	2,81E-06	
		Acétate d'éthyle	3,80E-04	

TABLEAU C1 - TAUX D'ÉMISSIONS DES SOURCES VISÉES POUR LE SCÉNARIO PRÉ-PROJET

No Source	Description	Substance	Taux d'émission	Taux d'émission annualisé
	des réservoirs de solvants usés	Acétate de méthyle	4,01E-05	
		Acétate de propyle	1,89E-05	
		Acétate de propylène glycol méthyle éther	1,51E-06	
		Acétone	3,14E-03	
		Acétonitrile	2,09E-04	
		Alcool éthylique	5,03E-04	
		Alcool isobutylique	6,46E-06	
		Alcool méthylique	1,13E-03	
		Benzène	8,05E-05	
		n-Butanol	1,13E-06	
		2-Butoxyéthanol	6,99E-08	
		sec-Butylbenzène	1,07E-06	
		Chloroforme	8,23E-04	
		3-Chlorophénol	1,32E-10	
		4-Chlorophénol	1,80E-11	
		p-Chlorotrifluorométhyl benzène	3,87E-07	
		Chlorure de méthylène	3,40E-03	
		o-Crésol	4,41E-10	
		m-Crésol	3,43E-10	
		p-Crésol	2,82E-09	
		Cyclohexane	1,36E-04	
		1,2-Dichlorobenzène	8,83E-07	
		1,3-Dichlorobenzène	1,32E-06	
		2,4+2,5-Dichlorophénol	1,84E-11	
		2,6-Dichlorophénol	2,59E-10	
		3,5-Dichlorophénol	1,22E-12	
		2,4-Diméthylphénol	3,80E-08	
		Éthylbenzène	2,05E-05	
		Éther de méthyle et de butyle tertiaire	8,85E-04	
		Heptane	5,58E-04	
		Isopropanol	1,89E-04	
		Isopropylbenzène (cumène)	2,94E-06	
		p-Isopropyltoluène (para-cymène)	8,49E-07	
		Méthyle n-amyl cétone	3,54E-07	
		Méthyl cyclohexane	3,47E-05	
		Méthyl éthyl cétone	1,45E-03	
		Méthyl isobutyle cétone	1,34E-04	
		Naphtalène	1,36E-07	
		4-Nitrophénol	6,15E-08	
		Pentachlorobenzène	1,63E-14	
		Pentachlorophénol	1,36E-12	
		Phénol	8,03E-09	
		n-Propanol	7,37E-06	
		n-Propylbenzène	2,12E-06	
		Propylène glycol monométhyléther	2,31E-07	
		1,2,3,4-Tétrachlorobenzène	1,43E-12	
		1,2,3,5 et 1,2,4,5-Tétrachlorobenzènes	6,70E-12	
		Tétrachloroéthylène	1,41E-05	
		2,3,4,6-Tétrachlorophénol	1,02E-11	
		Tétrahydro furanne	7,01E-05	
		Toluène	1,90E-04	
		1,2,4-Trichlorobenzène	8,92E-11	
		Trichloroéthène (Trichloroéthylène)	5,45E-05	
		1,2,4-Triméthylbenzène	1,76E-06	
		1,3,5-Triméthylbenzène	1,49E-06	
		Xylènes	6,89E-05	
8B	**Ouverture Nord du dôme (abri) des réservoirs de solvants usés**	Acétate de butyle	2,81E-06	
		Acétate d'éthyle	3,80E-04	
		Acétate de méthyle	4,01E-05	
		Acétate de propyle	1,89E-05	
		Acétate de propylène glycol méthyle éther	1,51E-06	
		Acétone	3,14E-03	
		Acétonitrile	2,09E-04	
		Alcool éthylique	5,03E-04	
		Alcool isobutylique	6,46E-06	

TABLEAU C1 - TAUX D'ÉMISSIONS DES SOURCES VISÉES POUR LE SCÉNARIO PRÉ-PROJET

No Source	Description	Substance	Taux d'émission	Taux d'émission annualisé
		Alcool méthylique	1,13E-03	
		Benzène	8,05E-05	
		n-Butanol	1,13E-06	
		2-Butoxyéthanol	6,99E-08	
		sec-Butylbenzène	1,07E-06	
		Chloroforme	8,23E-04	
		3-Chlorophénol	1,32E-10	
		4-Chlorophénol	1,80E-11	
		p-Chlorotrifluorométhyl benzène	3,87E-07	
		Chlorure de méthylène	3,40E-03	
		o-Crésol	4,41E-10	
		m-Crésol	3,43E-10	
		p-Crésol	2,82E-09	
		Cyclohexane	1,36E-04	
		1,2-Dichlorobenzène	8,83E-07	
		1,3-Dichlorobenzène	1,32E-06	
		2,4+2,5-Dichlorophénol	1,84E-11	
		2,6-Dichlorophénol	2,59E-10	
		3,5-Dichlorophénol	1,22E-12	
		2,4-Diméthylphénol	3,80E-08	
		Éthylbenzène	2,05E-05	
		Éther de méthyle et de butyle tertiaire	8,85E-04	
		Heptane	5,58E-04	
		Isopropanol	1,89E-04	
		Isopropylbenzène (cumène)	2,94E-06	
		p-Isopropyltoluène (para-cymène)	8,49E-07	
		Méthyle n-amyl cétone	3,54E-07	
		Méthyl cyclohexane	3,47E-05	
		Méthyl éthyl cétone	1,45E-03	
		Méthyl isobutyle cétone	1,34E-04	
		Naphtalène	1,36E-07	
		4-Nitrophénol	6,15E-08	
		Pentachlorobenzène	1,63E-14	
		Pentachlorophénol	1,36E-12	
		Phénol	8,03E-09	
		n-Propanol	7,37E-06	
		n-Propylbenzène	2,12E-06	
		Propylène glycol monométhyléther	2,31E-07	
		1,2,3,4-Tétrachlorobenzène	1,43E-12	
		1,2,3,5 et 1,2,4,5-Tétrachlorobenzènes	6,70E-12	
		Tétrachloroéthylène	1,41E-05	
		2,3,4,6-Tétrachlorophénol	1,02E-11	
		Tétrahydro furanne	7,01E-05	
		Toluène	1,90E-04	
		1,2,4-Trichlorobenzène	8,92E-11	
		Trichloroéthène (Trichloroéthylène)	5,45E-05	
		1,2,4-Triméthylbenzène	1,76E-06	
		1,3,5-Triméthylbenzène	1,49E-06	
		Xylènes	6,89E-05	

TABLEAU C2 - TAUX D'ÉMISSIONS DES SOURCES VISÉES POUR LE SCÉNARIO PROJET

No Source	Description	Substance	Taux d'émission	Taux d'émission annualisé
3	**Poste désemballage "labpacks"**	Acide chlorhydrique	2,02E-02	9,58E-04
		Acide nitrique	5,17E-02	2,46E-03
		Acide sulfurique	6,53E-08	3,10E-09
4	**Poste désemballage "labpacks"**	Acide chlorhydrique	2,02E-02	9,58E-04
		Acide nitrique	5,17E-02	2,46E-03
		Acide sulfurique	6,53E-08	3,10E-09
6	**Poste de percement de cannettes aérosols**	Acétate de butyle	1,22E-02	1,16E-03
		Acétone	2,43E-02	2,31E-03
		Éthylbenzène	4,06E-04	3,85E-05
		Toluène	1,01E-02	9,63E-04
		Xylène	2,03E-03	1,93E-04
9A	**Brûleur ATDU**	Particules	1,13E-02	
		NOx	1,27E-01	
		CO	1,39E-03	
		SO2	7,41E-04	
9B	**Brûleur ATDU**	Particules	1,13E-02	
		NOx	1,27E-01	
		CO	1,39E-03	
		SO2	7,41E-04	
10	**Oxydateur thermique**	Acétate de butyle	4,56E-05	
		Acétate d'éthyle	5,08E-04	
		Acétate de méthyle	2,83E-05	
		Acétate de propyle	1,00E-04	
		Acétate de propylène glycol méthyle éther	5,01E-04	
		Acétone	1,57E-03	
		Acétonitrile	3,56E-04	
		Alcool éthylique	1,25E-03	
		Alcool isobutylique	1,55E-04	
		Alcool méthylique	1,18E-03	
		Benzène	1,03E-04	
		n-Butanol	4,56E-05	
		2-Butoxyéthanol	2,73E-05	
		sec-Butylbenzène	1,30E-04	
		Chloroforme	6,11E-04	
		3-Chlorophénol	9,32E-08	
		4-Chlorophénol	2,07E-08	
		p-Chlorotrifluorométhyl benzène	9,12E-06	
		Chlorure de méthylène	8,56E-03	
		o-Crésol	7,25E-07	
		m-Crésol	6,21E-07	
		p-Crésol	1,24E-05	
		Cyclohexane	2,10E-04	
		1,2-Dichlorobenzène	1,30E-04	
		1,3-Dichlorobenzène	1,30E-04	
		2,4+2,5-Dichlorophénol	2,07E-08	
		2,6-Dichlorophénol	6,21E-07	
		3,5-Dichlorophénol	1,14E-07	
		2,4-Diméthylphénol	1,19E-04	
		Dioxines et furannes	1,36E-15	
		Éthylbenzène	3,19E-04	
		Éther de méthyle et de butyle tertiaire	4,96E-04	
		Heptane	1,99E-03	
		Isopropanol	9,02E-04	
		Isopropylbenzène (cumène)	1,30E-04	
		p-Isopropyltoluène (para-cymène)	1,30E-04	
		Méthyle n-amyl cétone	1,82E-05	
		Méthyl cyclohexane	1,19E-04	
		Méthyl éthyl cétone	2,03E-03	
		Méthyl isobutyle cétone	1,24E-03	
		Naphtalène	1,30E-04	
		4-Nitrophénol	2,07E-06	
		Pentachlorobenzène	1,29E-08	
		Pentachlorophénol	1,09E-06	
		Phénol	7,25E-06	
		n-Propanol	7,29E-05	
		n-Propylbenzène	1,30E-04	
		Propylène glycol monométhyléther	2,73E-05	
		1,2,3,4-Tétrachlorobenzène	1,55E-08	
		1,2,3,5 et 1,2,4,5-Tétrachlorobenzènes	4,19E-08	
		Tétrachloroéthylène	1,30E-04	
		2,3,4,6-Tétrachlorophénol	1,09E-07	
		Tétrahydro furanne	6,38E-05	
		Toluène	8,92E-04	
		1,2,4-Trichlorobenzène	4,40E-08	
		Trichloroéthène (Trichloroéthylène)	1,29E-04	
		1,2,4-Triméthylbenzène	1,87E-04	
		1,3,5-Triméthylbenzène	1,30E-04	
		Xylènes	1,24E-03	
		Particules	3,83E-03	
		NOx	1,75E-01	
		CO	4,23E-02	
		SO2	3,02E-04	
11	**Dépoussiéreur**	Particules (noir de carbone)	1,94E-03	

Annexe D CONCENTRATIONS AMBIANTES MAXIMALES PRÉDITES

TABLEAU D1 - RÉSULTATS DE LA DISPERSION ATMOSPHÉRIQUE POUR LE SCÉNARIO PRÉ-PROJET

Contaminants	Numéro C.A.S.	Période	Norme / Critère / SEPR (µg/m3)	Concentration initiale (µg/m3)	Concentration maximale (µg/m3)	Concentration maximale totale (µg/m3)	% Norme / Critère / SEPR (%)
Acétate de butyle	**123-86-4**	**4 min**	**30**	**0**	**320,4**	**320,4**	**1068%**
Acétate d'éthyle	**141-78-6**	**4 min**	**20**	**0**	**256,3**	**256,3**	**1282%**
Acétate de méthyle	79-20-9	4 min	5 150	0	23,5	23,5	0,5%
Acétate de méthyle	79-20-9	1 an	116	0	0,3	0,3	0,2%
Acétate de propyle	109-60-4	4 min	210	0	17,1	17,1	8%
Acétate de propylène glycol méthyle éther	108-65-6	1 an	1 000	0	1,2E-02	0,0	0,001%
Acétone	67-64-1	4 min	8 600	170	1945,1	2115,1	25%
Acétone	67-64-1	1 an	380	4	21,6	25,6	7%
Acétonitrile	75-05-8	1 an	3	0	1,4	1,4	48%
Acide chlorhydrique (1)	7647-01-0	4 min	1 150	0	579,7	579,7	50%
Acide chlorhydrique	7647-01-0	1 an	20	0	0,1	0,1	1%
Acide nitrique	**7697-37-2**	**1 heure**	**86**	**0**	**779,1**	**779,1**	**906%**
Acide sulfurique	7664-93-9	4 min	10	0	1,9E-03	0,0	0,02%
Acide sulfurique	7664-93-9	24 heures	4	0	1,3E-04	0,0	0,003%
Alcool éthylique	64-17-5	4 min	340	0	263,0	263,0	77%
Alcool isobutylique	78-83-1	4 min	33	0	6,2	6,2	19%
Alcool méthylique	67-56-1	4 min	5 500	120	464,1	584,1	11%
Alcool méthylique	67-56-1	1 an	50	10	7,7	17,7	35%
Benzène	71-43-2	24 heures	10	3	3,8	6,8	68%
n-Butanol	71-36-3	4 min	116	0	1,2	1,2	1%
2-Butoxyéthanol	111-76-2	4 min	210	0	0,1	0,1	0,06%
sec-Butylbenzène	135-98-8	1 heure	2 750	0	0,7	0,7	0,02%
sec-Butylbenzène	135-98-8	1 an	80	0	7,4E-03	0,0	0,01%
Chloroforme	**67-66-3**	**1 an**	**0,2**	**0**	**5,7**	**5,9**	**2445%**
3-Chlorophénol	108-43-0	1 heure	2,2	0	3,5E-05	0,0	0,002%
3-Chlorophénol	108-43-0	1 an	0,05	0	9,1E-07	0,0	0,002%
4-Chlorophénol	106-48-9	1 heure	6,7	0	5,4E-06	0,0	0,0001%
4-Chlorophénol	106-48-9	1 an	0,05	0	1,2E-07	0,0	0,0002%
p-Chlorotrifluorométhyl benzène	98-56-6	1 heure	1 830	0	0,2	0,2	0,01%
p-Chlorotrifluorométhyl benzène	98-56-6	1 an	34	0	2,7E-03	0,0	0,01%
Chlorure de méthylène	75-09-2	1 heure	14 000	3	1037,0	1040,0	7%
Chlorure de méthylène	**75-09-2**	**1 an**	**3,6**	**1**	**23,3**	**24,3**	**675%**
o-Crésol	95-48-7	4 min	6,0	0	6,4E-04	0,0	0,01%
m-Crésol	108-39-4	4 min	1,1	0	3,4E-04	0,0	0,03%
p-Crésol	106-44-5	4 min	0,9	0	6,8E-03	0,0	1%
Cyclohexane	110-82-7	4 min	1 435	40	85,7	125,7	9%
1,2-Dichlorobenzène	95-50-1	4 min	4 200	0	1,1	1,1	0,03%
1,2-Dichlorobenzène	95-50-1	1 an	40	0	6,1E-03	0,0	0,02%
1,3-Dichlorobenzène	541-73-1	24 heures	170	0	0,1	0,1	0,07%
1,3-Dichlorobenzène	541-73-1	1 an	0,9	0	9,2E-03	0,0	1%
2,4+2,5-Dichlorophénol	120-83-2 / 583-78-8	1 an	1,3	0	1,3E-07	0,0	0,00001%
2,6-Dichlorophénol	87-65-0	1 heure	4,64	0	7,0E-05	0,0	0,002%
2,6-Dichlorophénol	87-65-0	1 an	0,02	0	1,8E-06	0,0	0,01%
3,5-Dichlorophénol	591-35-5	1 an	1,3	0	8,9E-09	0,0	0,000001%
2,4+3,5-Dichlorophénol	120-83-2 / 583-78-8	1 an	1,3	0	1,4E-07	0,0	0,00001%
2,4-Diméthylphénol	105-67-9	1 heure	6,6	0	3,3E-02	0,0	1%
2,4-Diméthylphénol	105-67-9	1 an	0,006	0	2,7E-04	0,0	4%
Dioxines et furannes	1746-01-6	1 an	6,00E-08	4,00E-08		0,0	67%
Éthylbenzène	100-41-4	4 min	740	140	26,9	166,9	23%
Éthylbenzène	100-41-4	1 an	200	3	0,14	3,1	2%
Éther de méthyle et de butyle tertiaire	**1634-04-4**	**4 min**	**180**	**0**	**525,2**	**525,2**	**292%**
Heptane	142-82-5	4 min	2 740	60	418,8	478,8	17%
Isopropanol	67-63-0	4 min	7 800	0	136,5	136,5	2%
Isopropylbenzène (cumène)	98-82-8	4 min	40	0	3,1	3,1	8%
p-Isopropyltoluène (para-cymène)	99-87-6	4 min	12	0	1,1	1,1	9%
Méthyle n-amyl cétone	110-43-0	4 min	32	0	0,3	0,3	1%
Méthyl cyclohexane	108-87-2	1 heure	14,5	0	13,2	13,2	91%
Méthyl cyclohexane	108-87-2	1 an	1,8	0	0,24	0,2	13%
Méthyl éthyl cétone	**78-93-3**	**4 min**	**740**	**2**	**869,3**	**870,8**	**118%**
Méthyl isobutyle cétone	108-10-1	4 min	400	0	113,0	113,0	28%
Naphtalène	91-20-3	4 min	200	5	6,0E-02	5,1	3%
Naphtalène	91-20-3	1 an	3	0	9,3E-04	0,0	0,03%
4-Nitrophénol	100-02-7	1 heure	1,6	0	9,3E-03	0,0	1%
4-Nitrophénol	100-02-7	1 an	0,002	0	4,2E-04	0,0	21%
Pentachlorobenzène	608-93-5	1 an	0,3	0	1,3E-10	0,0	0,00000004%
Pentachlorophénol	87-86-5	1 an	0,001	0,0005	9,4E-09	0,0	50%
Phénol	108-95-2	4 min	160	0	1,1E-02	0,0	0,007%
n-Propanol	71-23-8	4 min	230	0	5,1	5,1	2%
n-Propylbenzène	103-65-1	4 min	19,0	0	2,3	2,3	12%

TABLEAU D1 - RÉSULTATS DE LA DISPERSION ATMOSPHÉRIQUE POUR LE SCÉNARIO PRÉ-PROJET

Contaminants	Numéro C.A.S.	Période	Norme / Critère / SEPR	Concentration initiale	Concentration maximale	Concentration maximale totale	% Norme / Critère / SEPR
n-Propylbenzène		1 an	2,8	0	1,5E-02	0,0	1%
Propylène glycol monométhyléther	107-98-2	4 min	5 530	0	1,5	1,5	0,03%
Propylène glycol monométhyléther	107-98-2	1 an	1 000	0	1,7E-03	0,0	0,0002%
1,2,3,4-Tétrachlorobenzène	634-66-2	1 an	1,5	0	1,0E-08	0,0	0,0000007%
1,2,3,5 et 1,2,4,5-Tétrachlorobenzènes	634-90-2 / 95-94-3	1 an	0,1	0	4,8E-08	0,0	0,00004%
Tétrachloroéthylène	127-18-4	1 an	2	1	9,8E-02	1,1	55%
2,3,4,6-Tétrachlorophénol	58-90-2	1 an	0,01	0	7,0E-08	0,0	0,0007%
Tétrahydro furanne	109-99-9	1 heure	1 470	0	20,5	20,5	1%
Toluène	**108-88-3**	**4 min**	**600**	**260**	**387,2**	**647,2**	**108%**
1,2,4-Trichlorobenzène	120-82-1	1 an	1	0,3	6,2E-07	0,3	30%
Trichloroéthène (Trichloroéthylène)	**79-01-6**	**1 an**	**0,4**	**0,3**	**0,38**	**0,7**	**169%**
1,2,4-Triméthylbenzène	95-63-6	4 min	590	140	2,1	142,1	24%
1,2,4-Triméthylbenzène	95-63-6	1 an	15	3	1,2E-02	3,0	20%
1,3,5-Triméthylbenzène	108-67-8	4 min	590	140	1,7	141,7	24%
1,3,5-Triméthylbenzène	108-67-8	1 an	15	3	1,0E-02	3,0	20%
Xylènes	1330-20-7	4 min	350	150	106,9	256,9	73%
Xylènes	1330-20-7	1 an	20	8	0,5	8,5	42%
Particules	N/A	24 heures	120	90	-	-	-
Particules fines (PM2.5)	N/A	24 heures	30	20	-	-	-
Particules (noir de carbone)	1333-86-4	1 heure	1	0	-	-	-
Particules (noir de carbone)	1333-86-4	1 an	0,3	0	-	-	-
NO2	10102-44-0	1 heure	414	150	-	-	-
NO2	10102-44-0	24 heures	207	100	-	-	-
NO2	10102-44-0	1 an	103	30	-	-	-
CO	630-08-0	1 heure	34 000	2 650	-	-	-
CO	630-08-0	8 heures	12 700	1 750	-	-	-
SO2	7446-09-5	4 min	1 050	150	-	-	-
SO2	7446-09-5	24 heures	288	50	-	-	-
SO2	7446-09-5	1 an	52	20	-	-	-

Note (1): Ce paramètre dépassait la norme lors de la modélisation menée en janvier 2022 avec l'ancien rapport bowen

TABLEAU D2 - RÉSULTATS DE LA DISPERSION ATMOSPHÉRIQUE POUR LE SCÉNARIO PROJET

Contaminants	Numéro C.A.S.	Période	Norme / Critère / SEPR	Concentration initiale	Concentration maximale	Concentration maximale totale	% Norme / Critère / SEPR
			(µg/m3)	(µg/m3)	(µg/m3)	(µg/m3)	(%)
Acétate de butyle	**123-86-4**	**4 min**	**30**	**0**	**24,5**	**24,5**	**82%**
Acétate d'éthyle	**141-78-6**	**4 min**	**20**	**0**	**0,3**	**0,3**	**2%**
Acétate de méthyle	79-20-9	4 min	5 150	0	0,02	0,02	0,0003%
Acétate de méthyle	79-20-9	1 an	116	0	0,0002	0,0002	0,0002%
Acétate de propyle	109-60-4	4 min	210	0	0,1	0,1	0,03%
Acétate de propylène glycol méthyle éther	108-65-6	1 an	1 000	0	3,5E-03	0,003	0,0003%
Acétone	67-64-1	4 min	8 600	170	48,9	218,9	3%
Acétone	67-64-1	1 an	380	4	0,1	4,1	1%
Acétonitrile	75-05-8	1 an	3	0	0,002	0,002	0,08%
Acide chlorhydrique	7647-01-0	4 min	1 150	0	81,5	81,5	7%
Acide chlorhydrique	7647-01-0	1 an	20	0	0,1	0,1	0,3%
Acide nitrique	**7697-37-2**	**1 heure**	**86**	**0**	**109,6**	**109,6**	**127%**
Acide sulfurique	7664-93-9	4 min	10	0	2,6E-04	2,6E-04	0,003%
Acide sulfurique	7664-93-9	24 heures	4	0	4,1E-05	4,1E-05	0,001%
Alcool éthylique	64-17-5	4 min	340	0	0,7	0,7	0,2%
Alcool isobutylique	78-83-1	4 min	33	0	0,1	0,1	0,3%
Alcool méthylique	67-56-1	4 min	5 500	120	0,7	120,7	2%
Alcool méthylique	67-56-1	1 an	50	10	0,01	10,0	20%
Benzène	71-43-2	24 heures	10	3	0,02	3,0	30%
n-Butanol	71-36-3	4 min	116	0	0,03	0,03	0,02%
2-Butoxyéthanol	111-76-2	4 min	210	0	0,02	0,02	0,01%
sec-Butylbenzène	135-98-8	1 heure	2 750	0	0,04	0,04	0,001%
sec-Butylbenzène	135-98-8	1 an	80	0	9,0E-04	9,0E-04	0,001%
Chloroforme	**67-66-3**	**1 an**	**0,2**	**0**	**0,004**	**0,2**	**85%**
3-Chlorophénol	108-43-0	1 heure	2,2	0	2,9E-05	2,9E-05	0,001%
3-Chlorophénol	108-43-0	1 an	0,05	0	6,5E-07	6,5E-07	0,001%
4-Chlorophénol	106-48-9	1 heure	6,7	0	6,5E-06	6,5E-06	0,0001%
4-Chlorophénol	106-48-9	1 an	0,05	0	1,4E-07	1,4E-07	0,0003%
p-Chlorotrifluorométhyl benzène	98-56-6	1 heure	1 830	0	0,003	0,003	0,0002%
p-Chlorotrifluorométhyl benzène	98-56-6	1 an	34	0	6,3E-05	6,3E-05	0,0002%
Chlorure de méthylène	75-09-2	1 heure	14 000	3	2,7	5,7	0,04%
Chlorure de méthylène	**75-09-2**	**1 an**	**3,6**	**1**	**0,1**	**1,1**	**29%**
o-Crésol	95-48-7	4 min	6,0	0	4,3E-04	4,3E-04	0,01%
m-Crésol	108-39-4	4 min	1,1	0	3,7E-04	3,7E-04	0,03%
p-Crésol	106-44-5	4 min	0,9	0	7,4E-03	7,4E-03	1%
Cyclohexane	110-82-7	4 min	1 435	40	0,1	40,1	3%
1,2-Dichlorobenzène	95-50-1	4 min	4 200	0	0,1	0,1	0,002%
1,2-Dichlorobenzène	95-50-1	1 an	40	0	9,0E-04	9,0E-04	0,002%
1,3-Dichlorobenzène	541-73-1	24 heures	170	0	0,02	0,02	0,01%
1,3-Dichlorobenzène	541-73-1	1 an	0,9	0	9,0E-04	9,0E-04	0,1%
2,4+2,5-Dichlorophénol	120-83-2 / 583-78-8	1 an	1,3	0	1,4E-07	1,4E-07	0,00001%
2,6-Dichlorophénol	87-65-0	1 heure	4,64	0	1,9E-04	1,9E-04	0,004%
2,6-Dichlorophénol	87-65-0	1 an	0,02	0	4,3E-06	4,3E-06	0,02%
3,5-Dichlorophénol	591-35-5	1 an	1,3	0	7,9E-07	7,9E-07	0,0001%
2,4+3,5-Dichlorophénol	120-83-2 / 583-78-8	1 an	1,3	0	9,4E-07	9,4E-07	0,00007%
2,4-Diméthylphénol	105-67-9	1 heure	6,6	0	3,7E-02	3,7E-02	1%
2,4-Diméthylphénol	105-67-9	1 an	0,006	0	8,3E-04	8,3E-04	14%
Dioxines et furannes	1746-01-6	1 an	6,00E-08	4,00E-08	9,4E-15	4,0E-08	67%
Éthylbenzène	100-41-4	4 min	740	140	0,8	140,8	19%
Éthylbenzène	100-41-4	1 an	200	3	0,002	3,0	2%
Éther de méthyle et de butyle tertiaire	**1634-04-4**	**4 min**	**180**	**0**	**0,3**	**0,3**	**0,2%**
Heptane	142-82-5	4 min	2 740	60	1,2	61,2	2%
Isopropanol	67-63-0	4 min	7 800	0	0,5	0,5	0,01%
Isopropylbenzène (cumène)	98-82-8	4 min	40	0	0,1	0,1	0,2%
p-Isopropyltoluène (para-cymène)	99-87-6	4 min	12	0	0,1	0,1	1%
Méthyle n-amyl cétone	110-43-0	4 min	32	0	0,01	0,01	0,03%
Méthyl cyclohexane	108-87-2	1 heure	14,5	0	0,04	0,04	0,3%
Méthyl cyclohexane	108-87-2	1 an	1,8	0	0,001	0,001	0,05%
Méthyl éthyl cétone	**78-93-3**	**4 min**	**740**	**2**	**1,2**	**2,7**	**0,4%**
Méthyl isobutyle cétone	108-10-1	4 min	400	0	0,7	0,7	0,2%
Naphtalène	91-20-3	4 min	200	5	7,8E-02	5,1	3%
Naphtalène	91-20-3	1 an	3	0	9,0E-04	9,0E-04	0,03%
4-Nitrophénol	100-02-7	1 heure	1,6	0	6,5E-04	6,5E-04	0,04%
4-Nitrophénol	100-02-7	1 an	0,002	0	1,4E-05	1,4E-05	1%
Pentachlorobenzène	608-93-5	1 an	0,3	0	9,0E-08	9,0E-08	0,00003%
Pentachlorophénol	87-86-5	1 an	0,001	0,0005	7,6E-06	5,1E-04	51%
Phénol	108-95-2	4 min	160	0	4,3E-03	4,3E-03	0,003%
n-Propanol	71-23-8	4 min	230	0	0,04	0,04	0,02%
n-Propylbenzène	103-65-1	4 min	19,0	0	0,1	0,1	0,4%

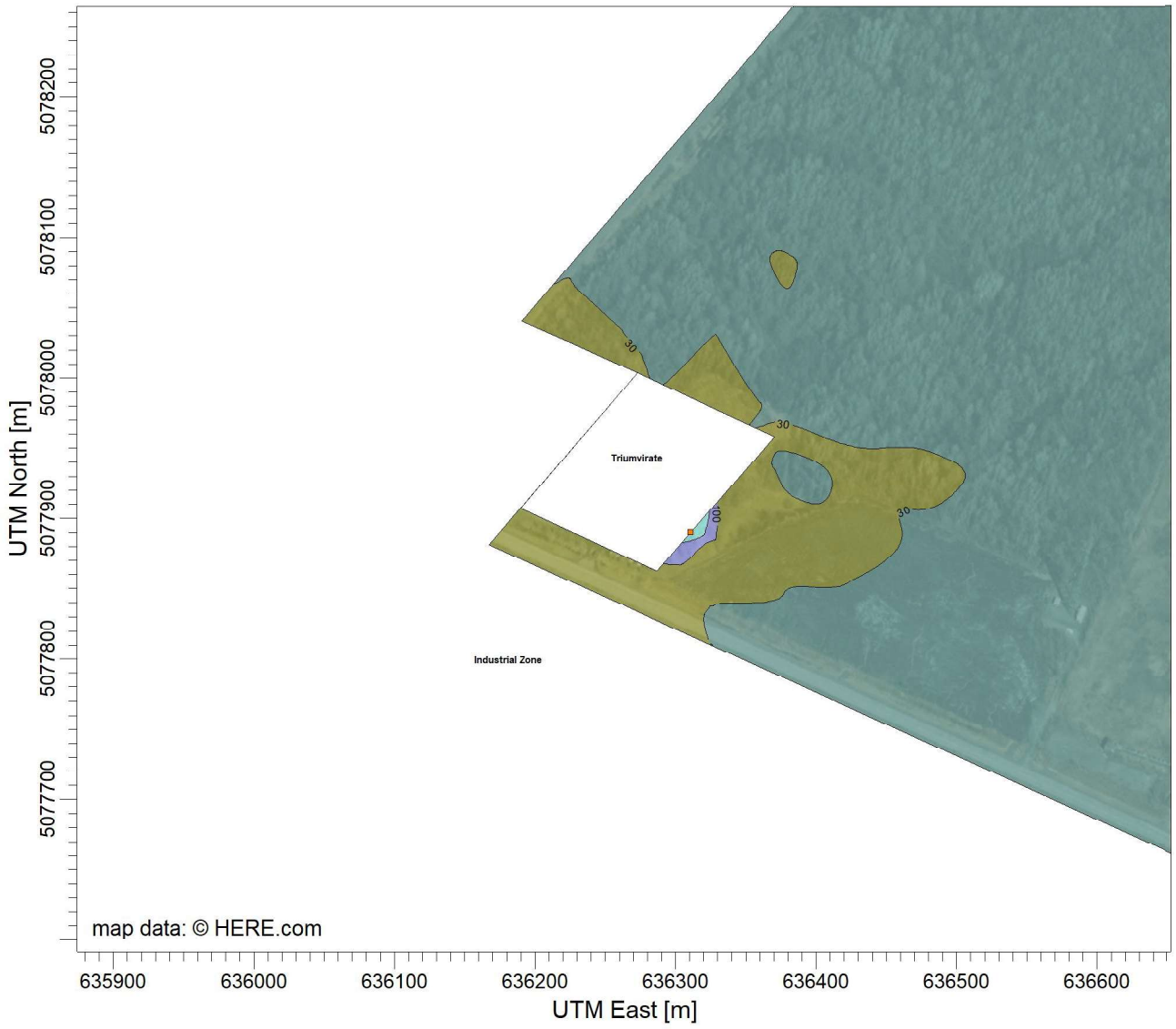
TABLEAU D2 - RÉSULTATS DE LA DISPERSION ATMOSPHÉRIQUE POUR LE SCÉNARIO PROJET

Contaminants	Numéro C.A.S.	Période	Norme / Critère / SEPR	Concentration initiale	Concentration maximale	Concentration maximale totale	% Norme / Critère / SEPR
n-Propylbenzène	103-65-1	1 an	2,8	0	9,0E-04	9,0E-04	0,03%
Propylène glycol monométhyléther	107-98-2	4 min	5 530	0	0,02	0,02	0,0003%
Propylène glycol monométhyléther	107-98-2	1 an	1 000	0	1,9E-04	1,9E-04	0,00002%
1,2,3,4-Tétrachlorobenzène	634-66-2	1 an	1,5	0	1,1E-07	1,1E-07	0,000007%
1,2,3,5 et 1,2,4,5-Tétrachlorobenzènes	634-90-2 / 95-94-3	1 an	0,1	0	2,9E-07	2,9E-07	0,0002%
Tétrachloroéthylène	127-18-4	1 an	2	1	9,0E-04	1,0E+00	50%
2,3,4,6-Tétrachlorophénol	58-90-2	1 an	0,01	0	7,6E-07	7,6E-07	0,008%
Tétrahydro furanne	109-99-9	1 heure	1 470	0	0,02	0,02	0,001%
Toluène	**108-88-3**	**4 min**	**600**	**260**	**20,4**	**280,4**	**47%**
1,2,4-Trichlorobenzène	120-82-1	1 an	1	0,3	3,1E-07	0,3	30%
Trichloroéthène (Trichloroéthylène)	**79-01-6**	**1 an**	**0,4**	**0,3**	**0,0009**	**0,3**	**75%**
1,2,4-Triméthylbenzène	95-63-6	4 min	590	140	0,1	140,1	24%
1,2,4-Triméthylbenzène	95-63-6	1 an	15	3	1,3E-03	3,0	20%
1,3,5-Triméthylbenzène	108-67-8	4 min	590	140	0,1	140,1	24%
1,3,5-Triméthylbenzène	108-67-8	1 an	15	3	9,0E-04	3,0	20%
Xylènes	1330-20-7	4 min	350	150	4,4	154,4	44%
Xylènes	1330-20-7	1 an	20	8	0,01	8,0	40%
Particules	N/A	24 heures	120	90	3,6	93,6	78%
Particules fines (PM2.5)	N/A	24 heures	30	20	3,6	23,6	79%
Particules (noir de carbone)	**1333-86-4**	**1 heure**	**1**	**0**	**0,4**	**0,4**	**37%**
Particules (noir de carbone)	1333-86-4	1 an	0,3	0	0,01	0,01	3%
NO2	10102-44-0	1 heure	414	150	95,3	245,3	59%
NO2	10102-44-0	24 heures	207	100	46,2	146,2	71%
NO2	10102-44-0	1 an	103	30	5,5	35,5	35%
CO	630-08-0	1 heure	34 000	2 650	13,6	2663,6	8%
CO	630-08-0	8 heures	12 700	1 750	7,8	1757,8	14%
SO2	7446-09-5	4 min	1 050	150	0,7	150,7	14%
SO2	7446-09-5	24 heures	288	50	0,2	50,2	17%
SO2	7446-09-5	1 an	52	20	0,03	20,0	39%

Annexe E CARTES D'ISOPLÈTHES DES CONCENTRATIONS AMBIANTES MAXIMALES PRÉDITES

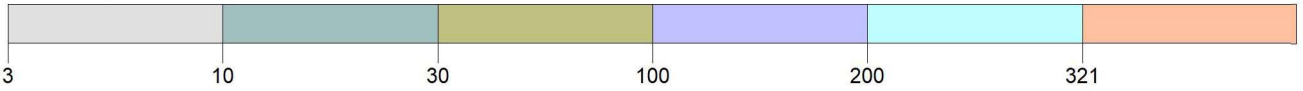
PROJECT TITLE:

Triumvirate Environmental
4-min Concentration Plot for Butyl Acetate



PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL ug/m^3

Max: 321 [ug/m^3] at (636310.63, 5077890.02)



COMMENTS: 4-min norm: 30 ug/m3 Initial Concentration: 0 ug/m3 Orange Square represents the location of the maximum concentration. Blue triangles represent the locations of the sensitive receptors.	SOURCES: **14**	COMPANY NAME: **Stantec Consulting Ltd.**	
	RECEPTORS: **1855**		
	OUTPUT TYPE: **Concentration**	SCALE: 1:4,898 0 0.1 km	
	MAX: **321 ug/m^3**	DATE: **12/22/2022**	PROJECT NO.:

PROJECT TITLE:

Triumvirate Environmental
4-min Concentration Plot for Butyl Acetate



PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL ug/m^3

Max: 24.5 [ug/m^3] at (636254.37, 5077877.51)

0.2 10.0 24.5

COMMENTS: 4-min norm: 30 ug/m3 Initial Concentration: 0 ug/m3 Orange square represents the location of the maximum concentration. Blue Triangles represent the location of sensitive receptors.	SOURCES: **14**	COMPANY NAME: **Stantec Consulting Ltd.**	
	RECEPTORS: **1855**		
	OUTPUT TYPE: **Concentration**	SCALE: 1:17,364 0 0.5 km	
	MAX: **24.5 ug/m^3**	DATE: **12/22/2022**	PROJECT NO.: